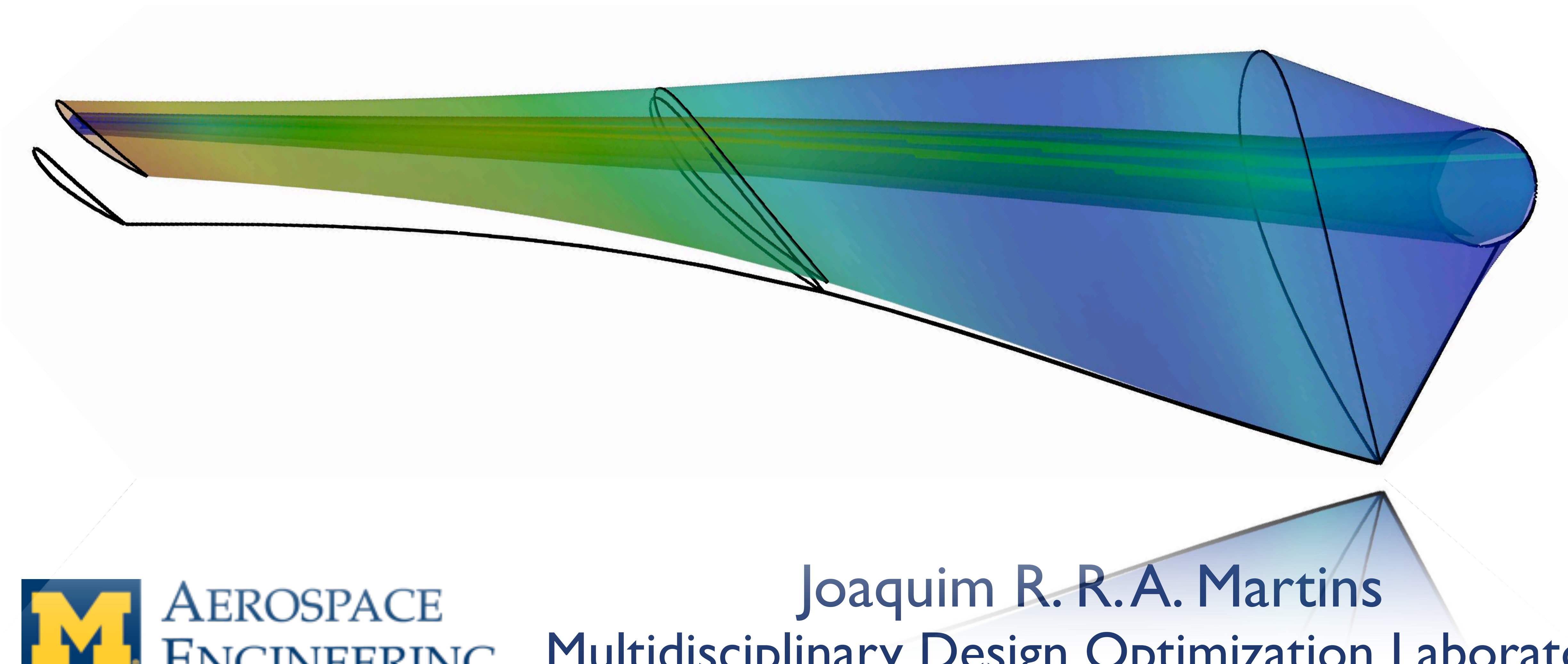
# Towards Optimal Aeroelastic Tailoring of Wind Turbine Blades



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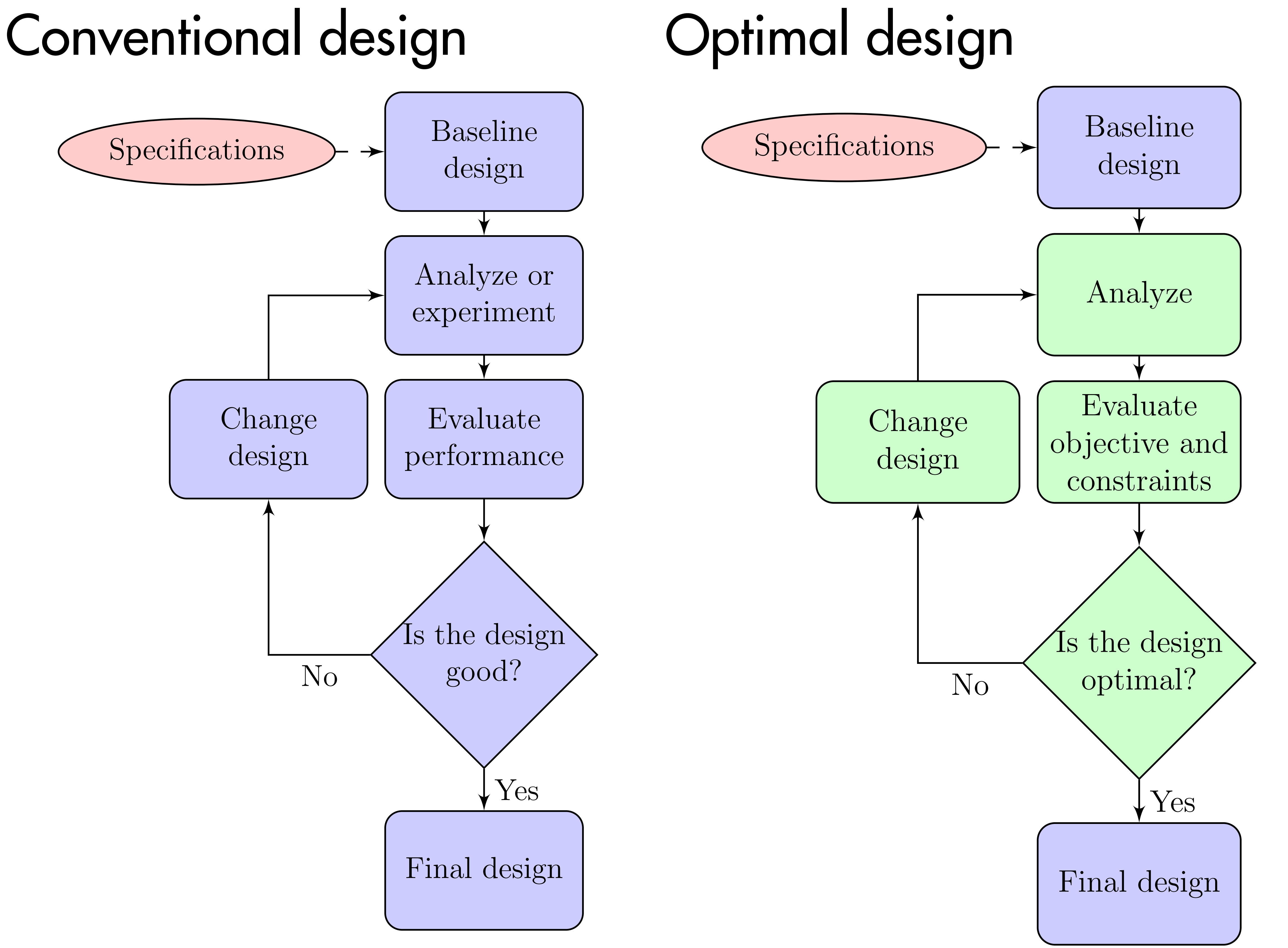
2nd NREL Systems Engineering Workshop
Broomfield, CO, Jan 29, 2013

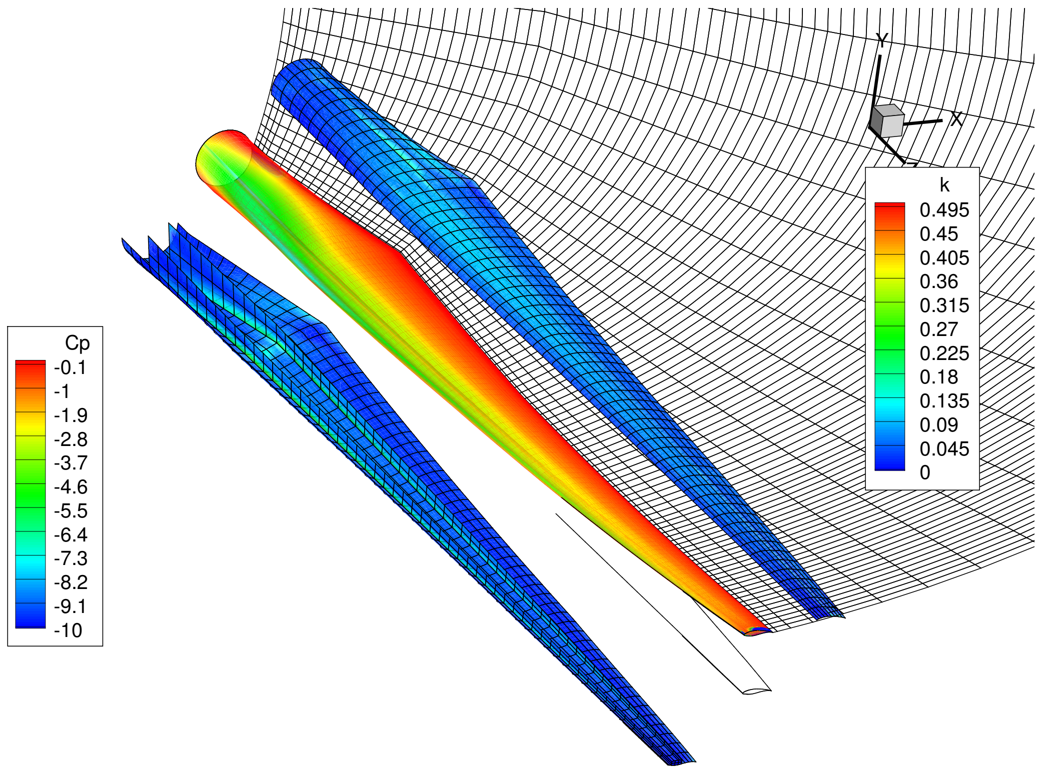
# What is Multidisciplinary Design Optimization – MDO?



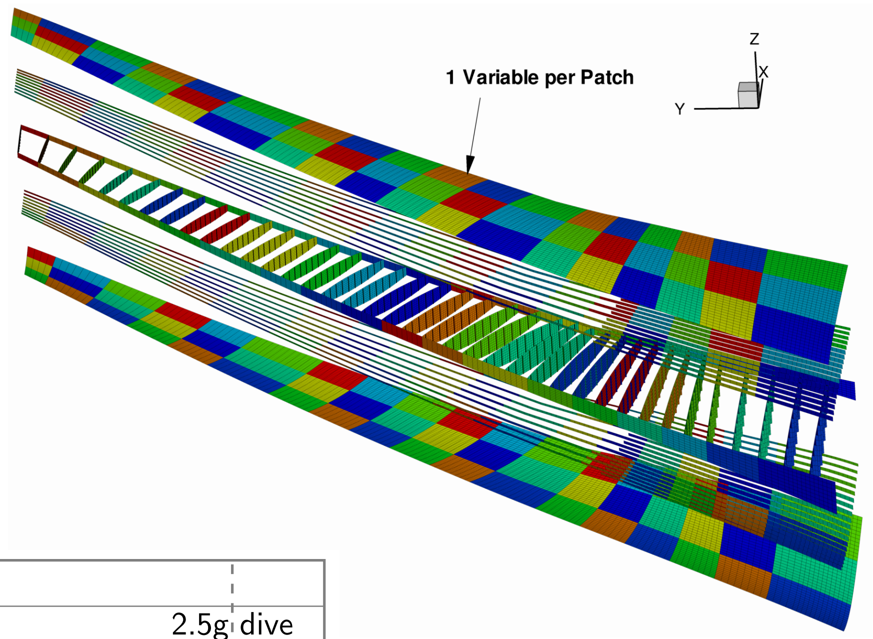

[Martins and Lambe, *AIAAJ* 2013]

# MDO Challenges:

1. Multiple highly coupled systems

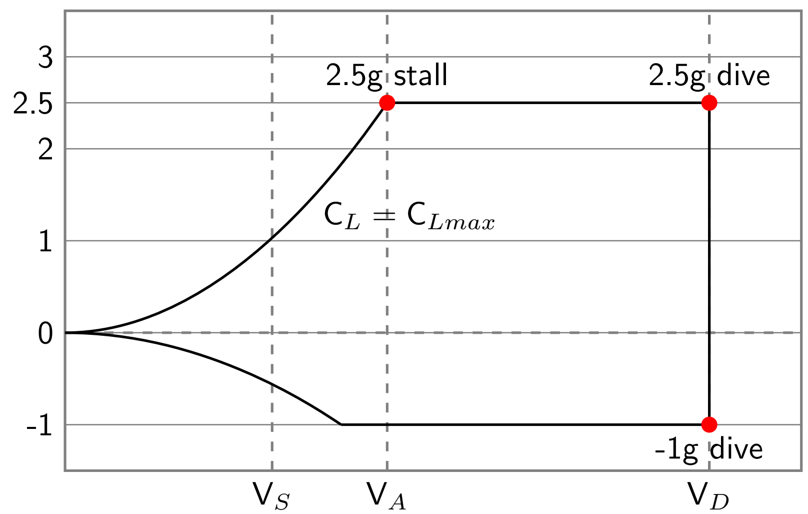


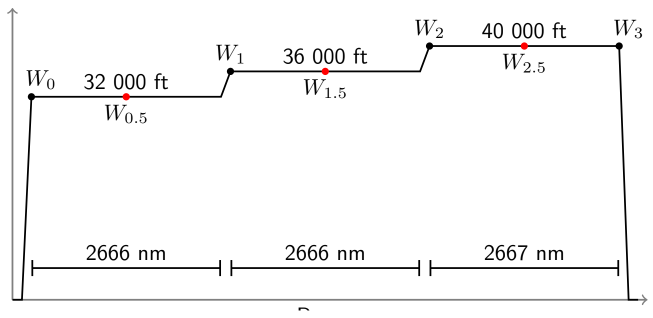

2. High computational cost of analysis




3. Large numbers of design variables, design points and constraints

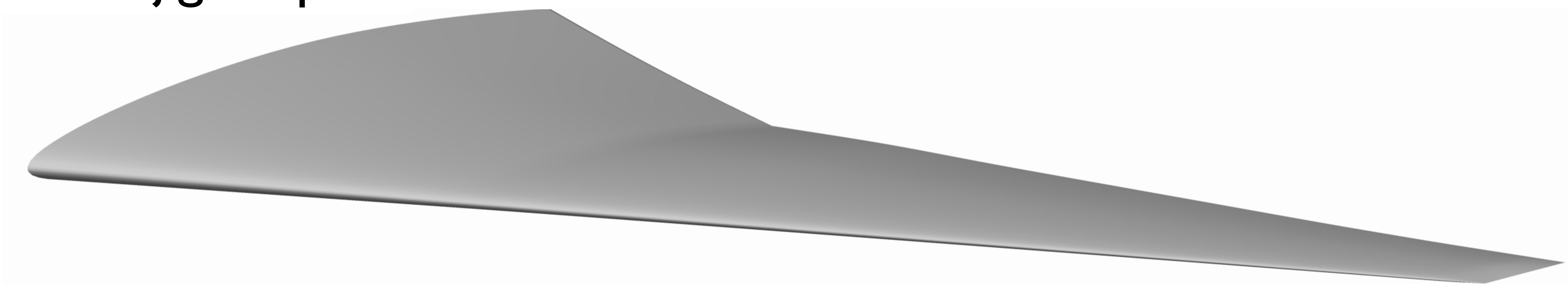
4. Relevant problem formulation



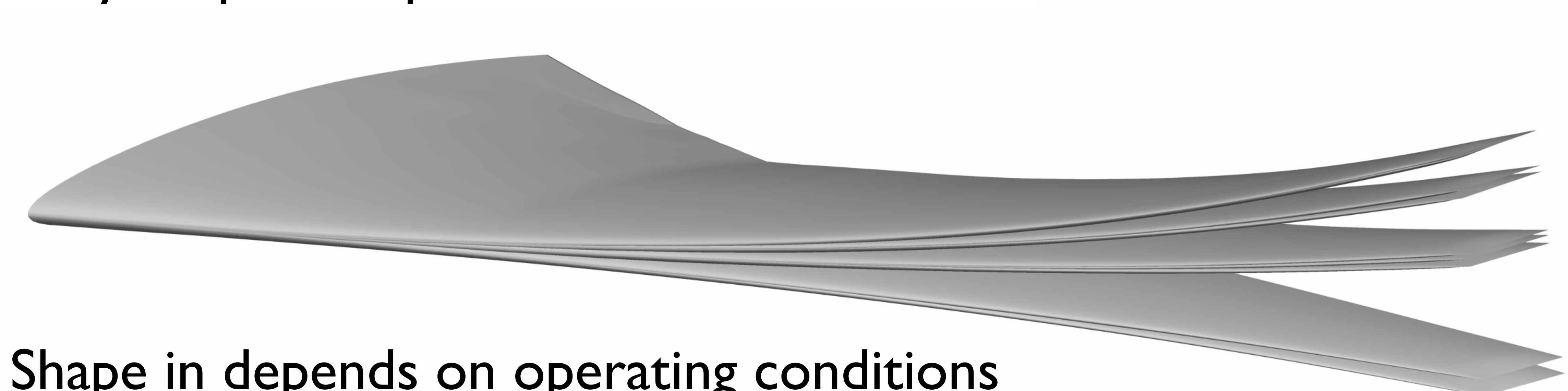



# Aerostructural coupling is particularly important in lifting surface design

One jig shape



Many shapes in operation



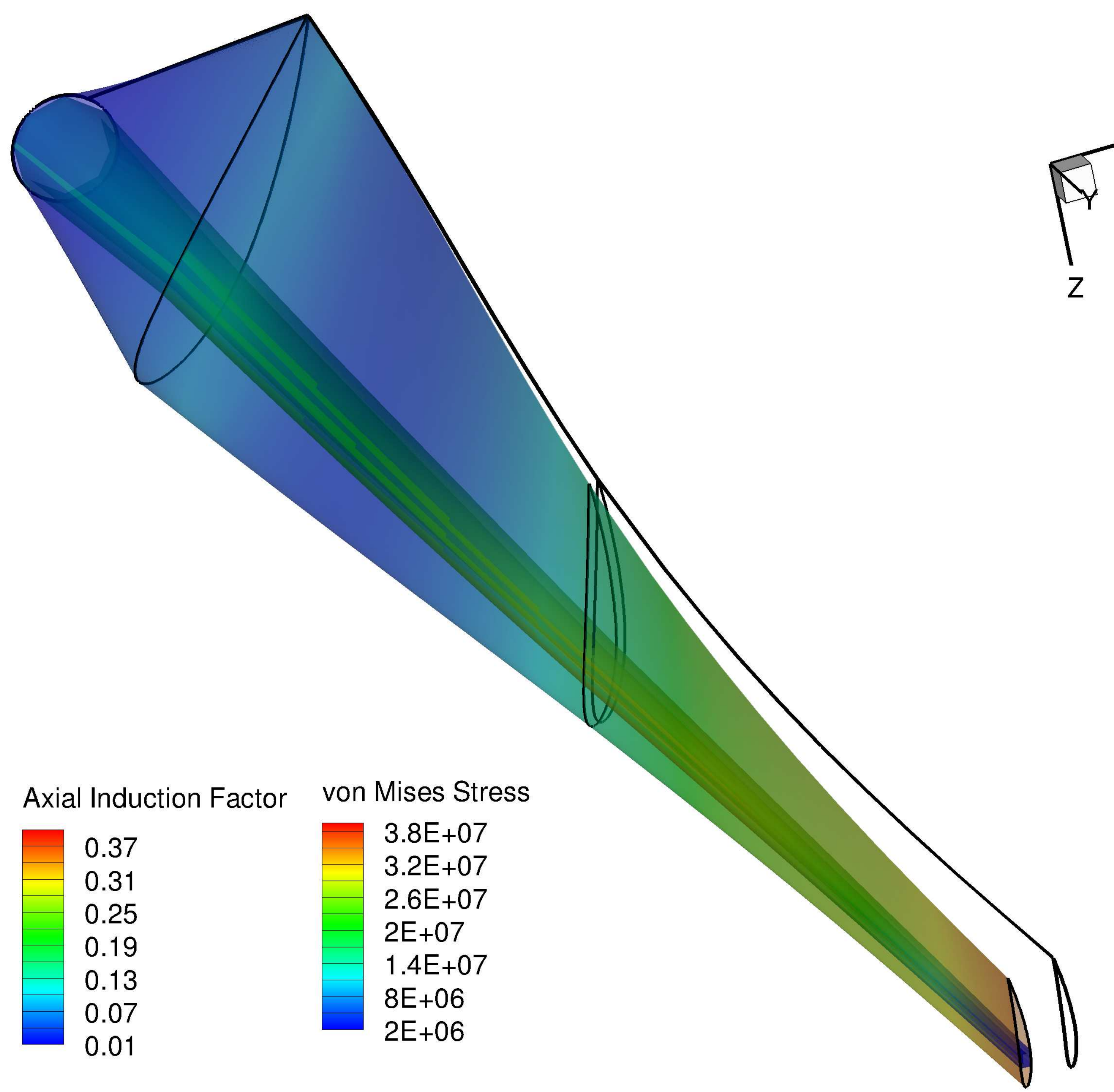
- Shape in depends on operating conditions
- Can result in poor performance if not accounted for...
- ...but can also be used to our advantage—aeroelastic tailoring

# Aerostructural Optimization of a Wind Turbine Blade Considering Site-Specific Winds

[Kenway and Martins, AIAA 2008-6025]

# Aerostructural Analysis

- BEM aerodynamic analysis with Prandtl correction and post-stall
- Structural analysis uses beam finite elements
- Aerodynamics and structures are coupled to obtain an aerostructural solution corresponding to a deflected blade
- The annual energy production (AEP) is computed based on aerostructural solutions for the various wind speeds

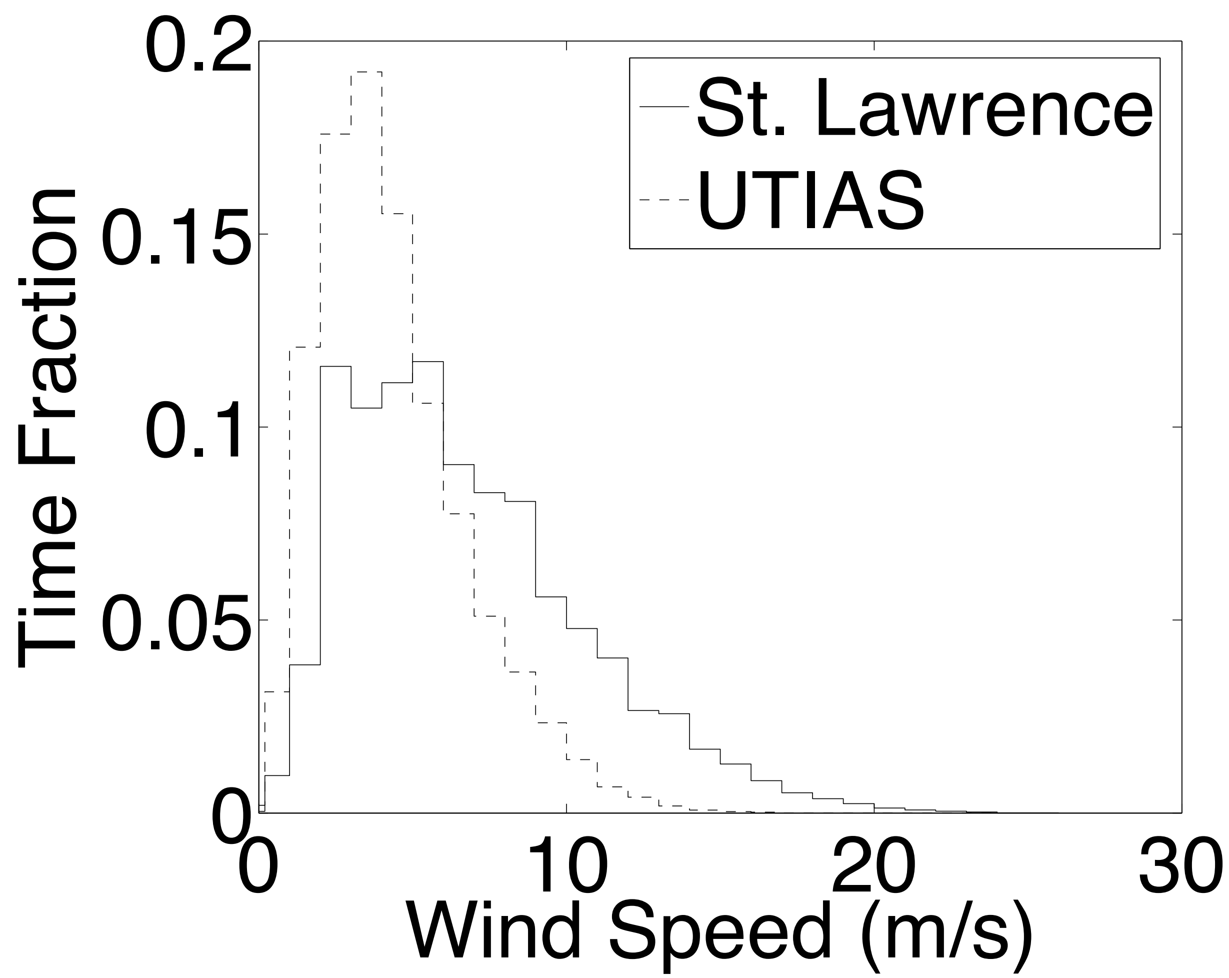


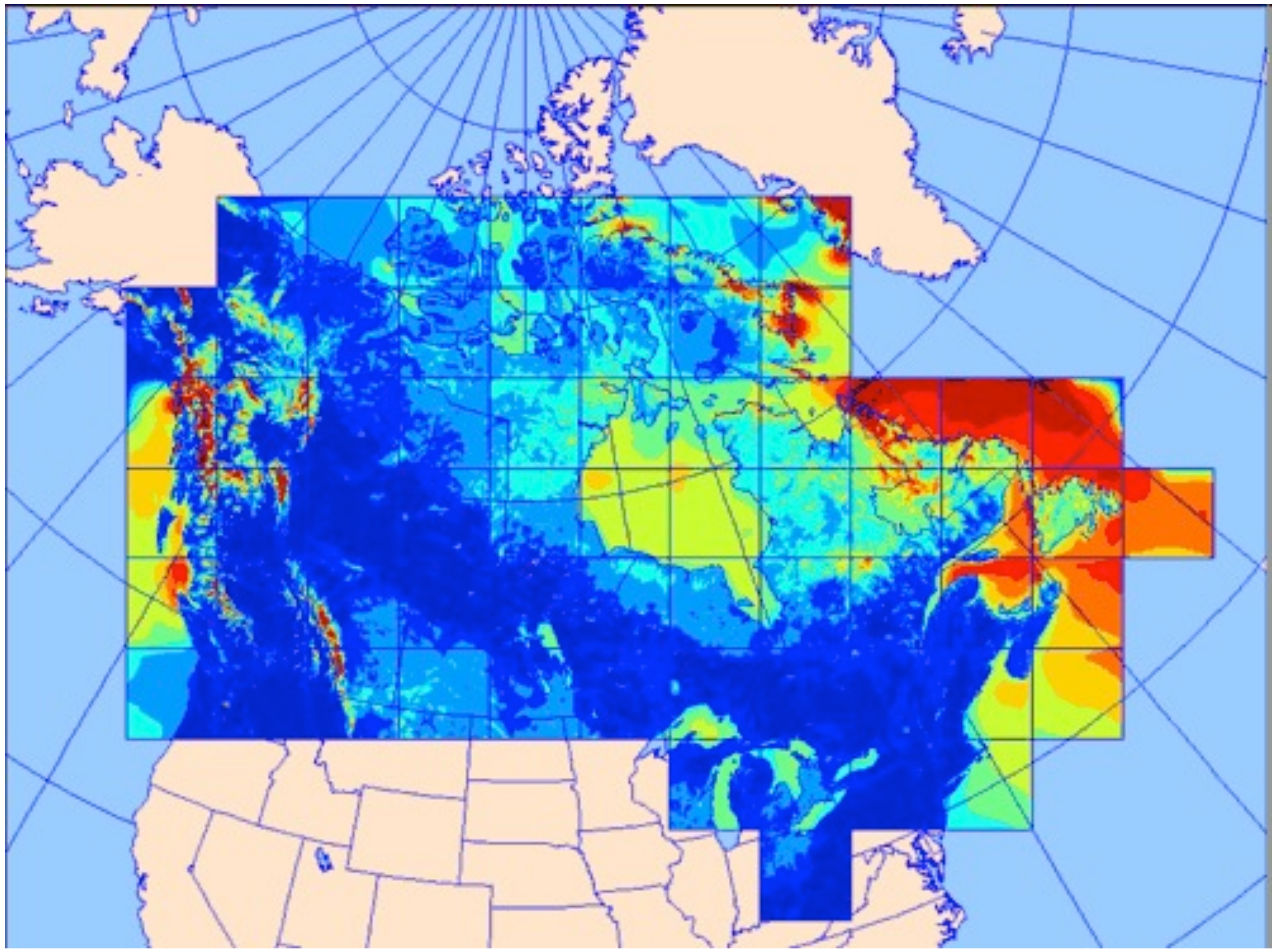
# Design Case: Small Urban Wind Turbine

- Wes5 Tulipo
- 5 kW power
- 5 m diameter
- 3 blades, fixed pitch
- Variable speed

# Site-Specific Wind Distributions

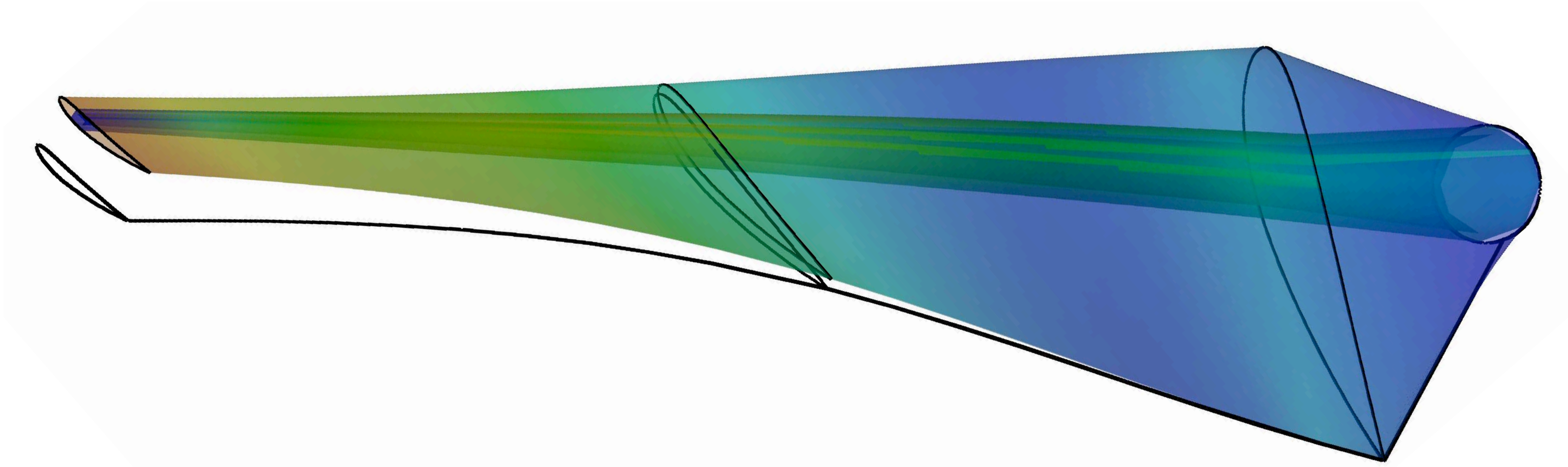
- Canadian Wind Energy Atlas gives wind velocity distributions for the whole country
- Two sites:
  - UTIAS, Toronto
  - St. Lawrence, Newfoundland

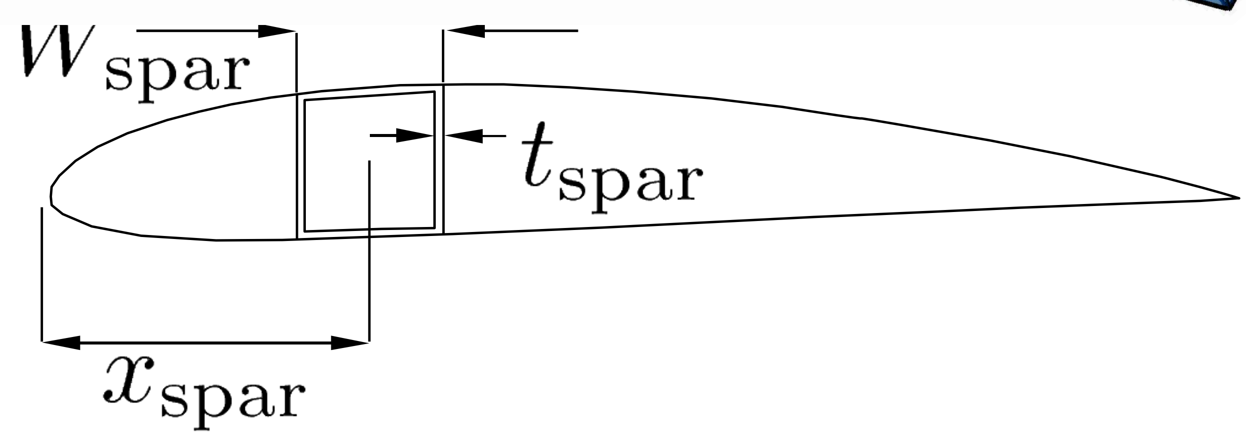


# Design Variables

- Chord distribution
- Twist distribution
- Spar thickness
- Spar width
- Airfoil thickness
- Rotation rate






| Design Variable | Count | Lower Limit | Upper Limit |
|---|---|---|---|
| Chord | 4 | .05 m | .40 m |
| Twists | 4 | -75 deg | 75 deg |
| $W_{\text{spar}}$ | 4 | 4% | 30% |
| $t_{\text{spar}}$ | 4 | 0.3 mm | 10mm |
| $t_{\text{foil}}$ | 3 | 6% | 20% |
| $\Omega$ | varies (12) | 7.5 rad/s | 14.7 rad/s |

# Design Constraints

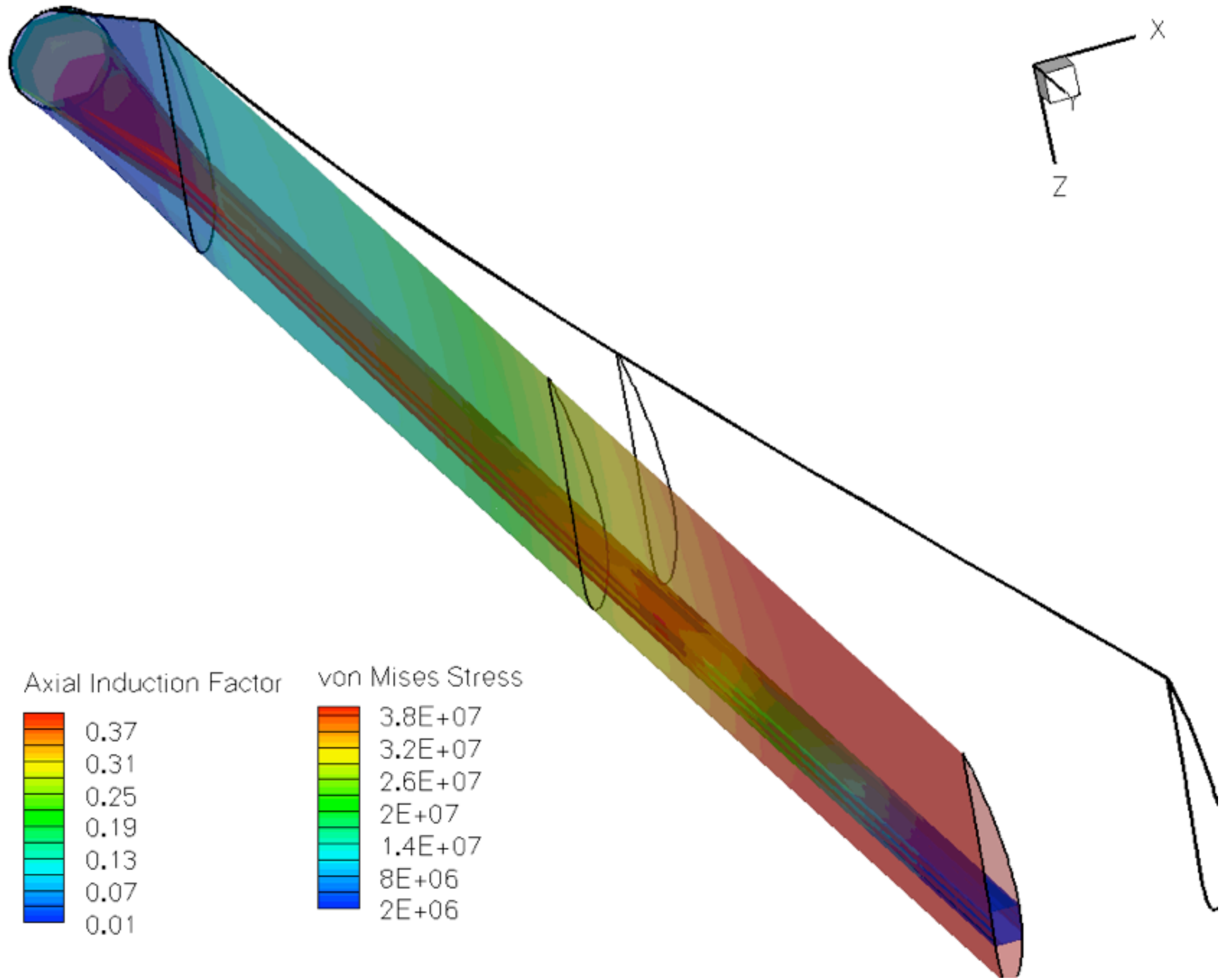
**Stresses:** Upper bound on von Mises stress for each finite element

**Cost:** This is constrained by setting upper bounds for spar mass and blade surface area

**Maximum power:** Power transmitted to the generator must not exceed its capacity

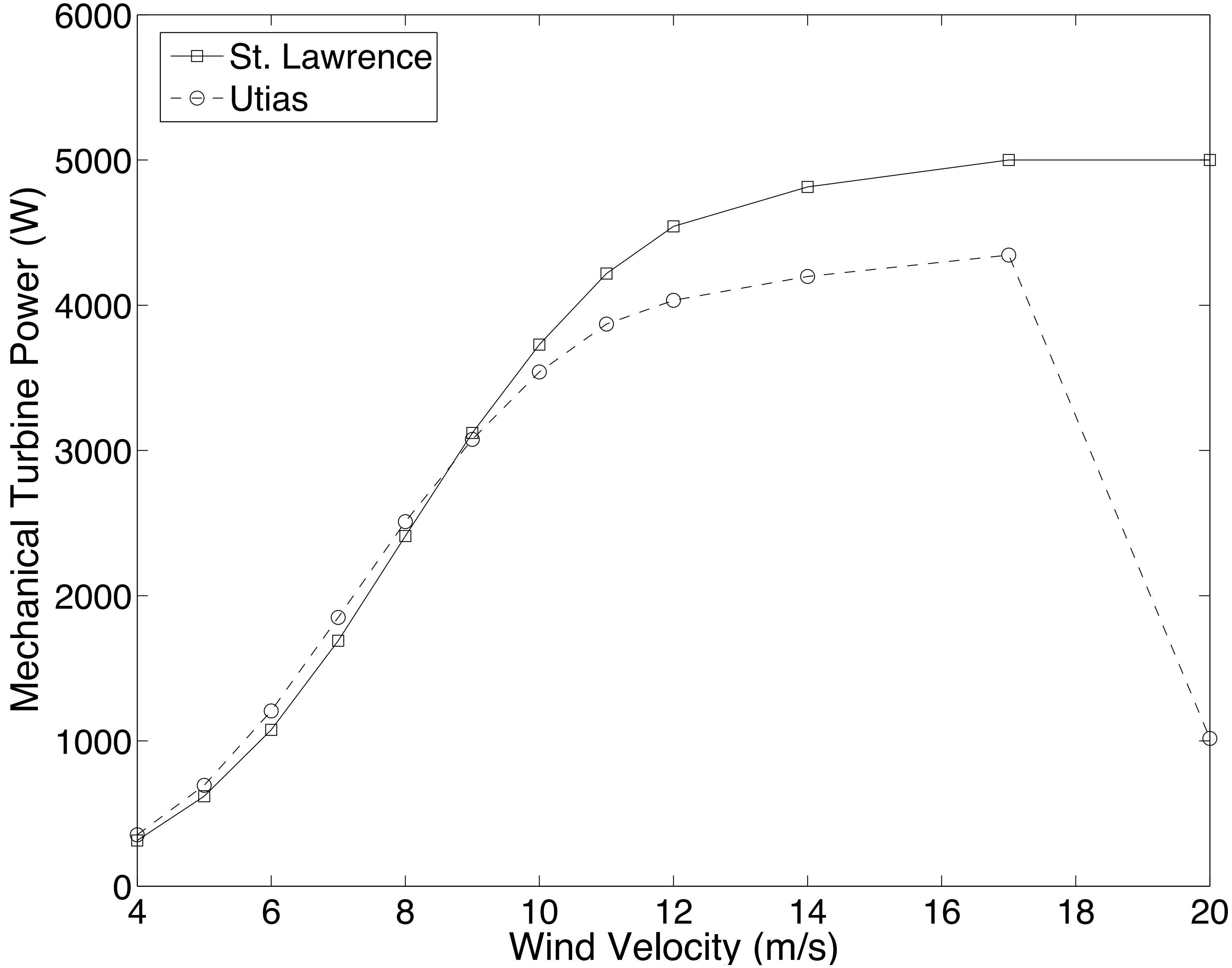
**Geometry:** Constrained to prevent non-physical geometries

| Constraint | Minimum | Maximum |
|---|---|---|
| Stress | - | 40MPa |
| Spar Mass | - | 3.7kg |
| Surface Area | - | $0.83\mathrm{m}^2$ |
| Power | - | 5000 W |
| Geometry | 0.5mm | - |



X
Y
Z
Axial Induction Factor
0.37
0.31
0.25
0.19
0.13
0.07
0.01
von Mises Stress
3.8E+07
3.2E+07
2.6E+07
2E+07
1.4E+07
8E+06
2E+06

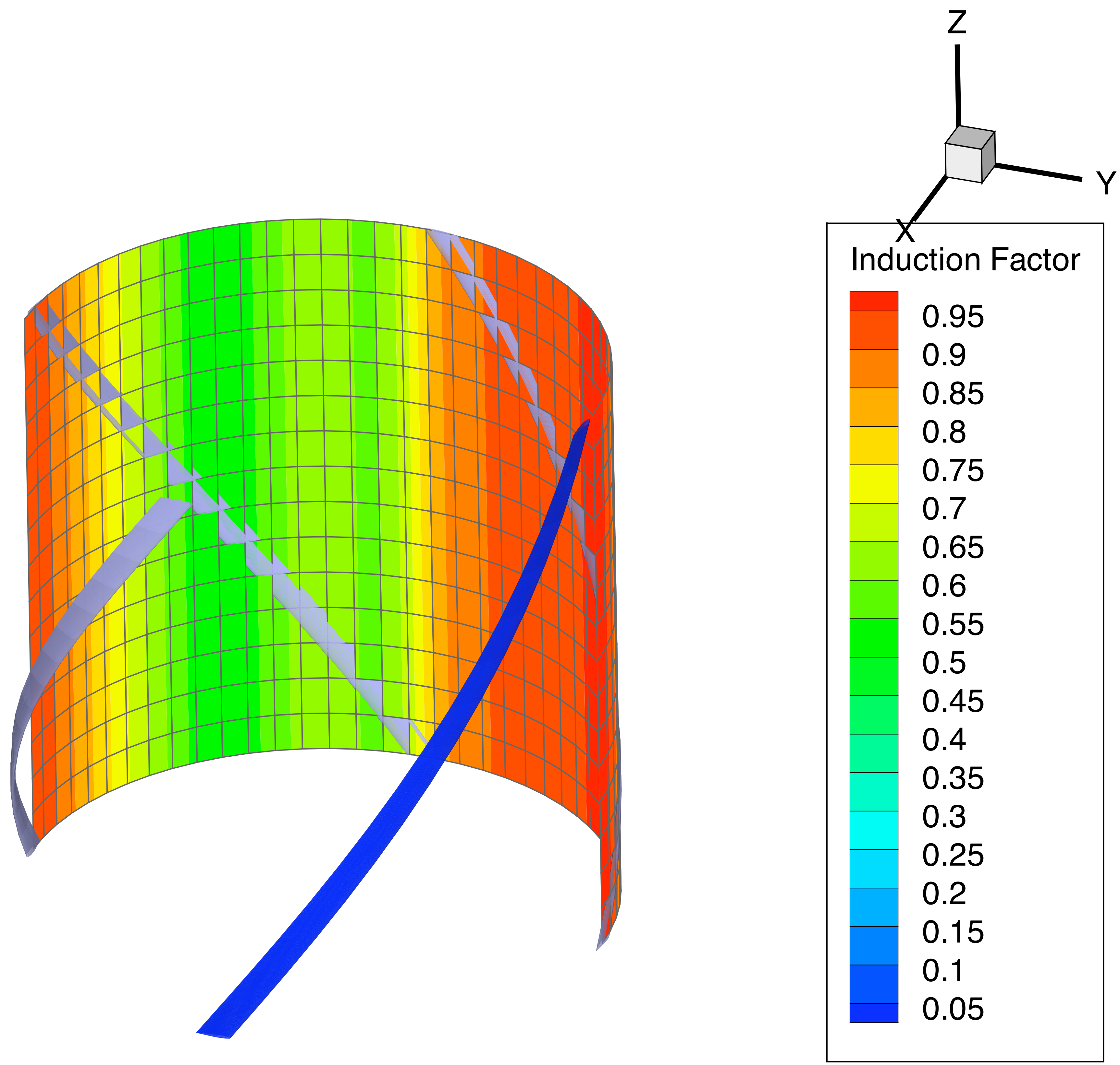
# Power of Optimized Turbines



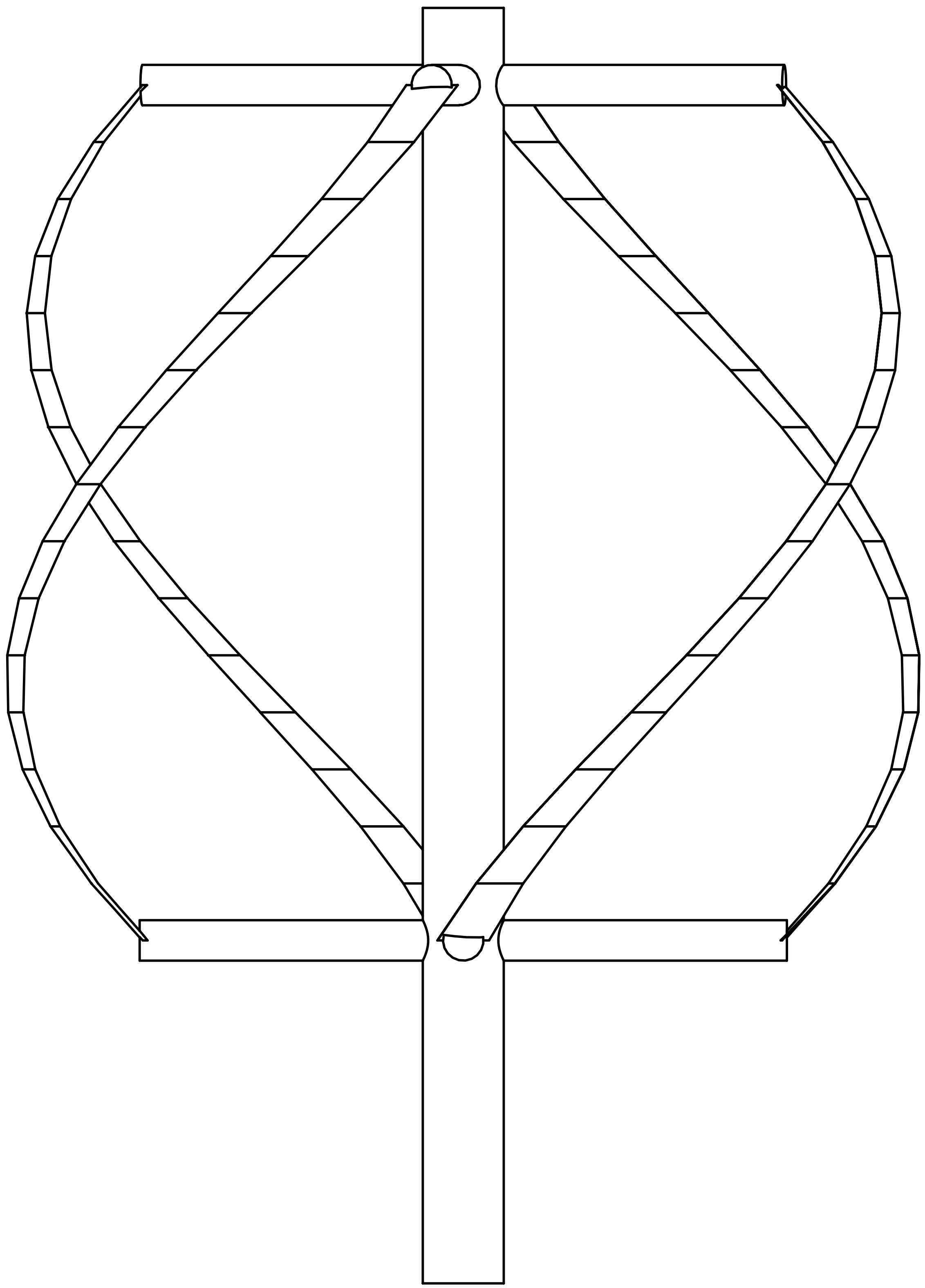

| Location | $\bar{P}_{\mathrm{init}}$ (W) | $\bar{P}_{\mathrm{opt}}$ (W) | $\bar{P}_{\mathrm{other-opt}}$ (W) | Site-specific increase |
|---|---|---|---|---|
| St. Lawrence | 1566.1 | 1984.5 | 1905.1 | 4.17% |
| UTIAS | 660.2 | 853.3 | 826.0 | 3.31% |

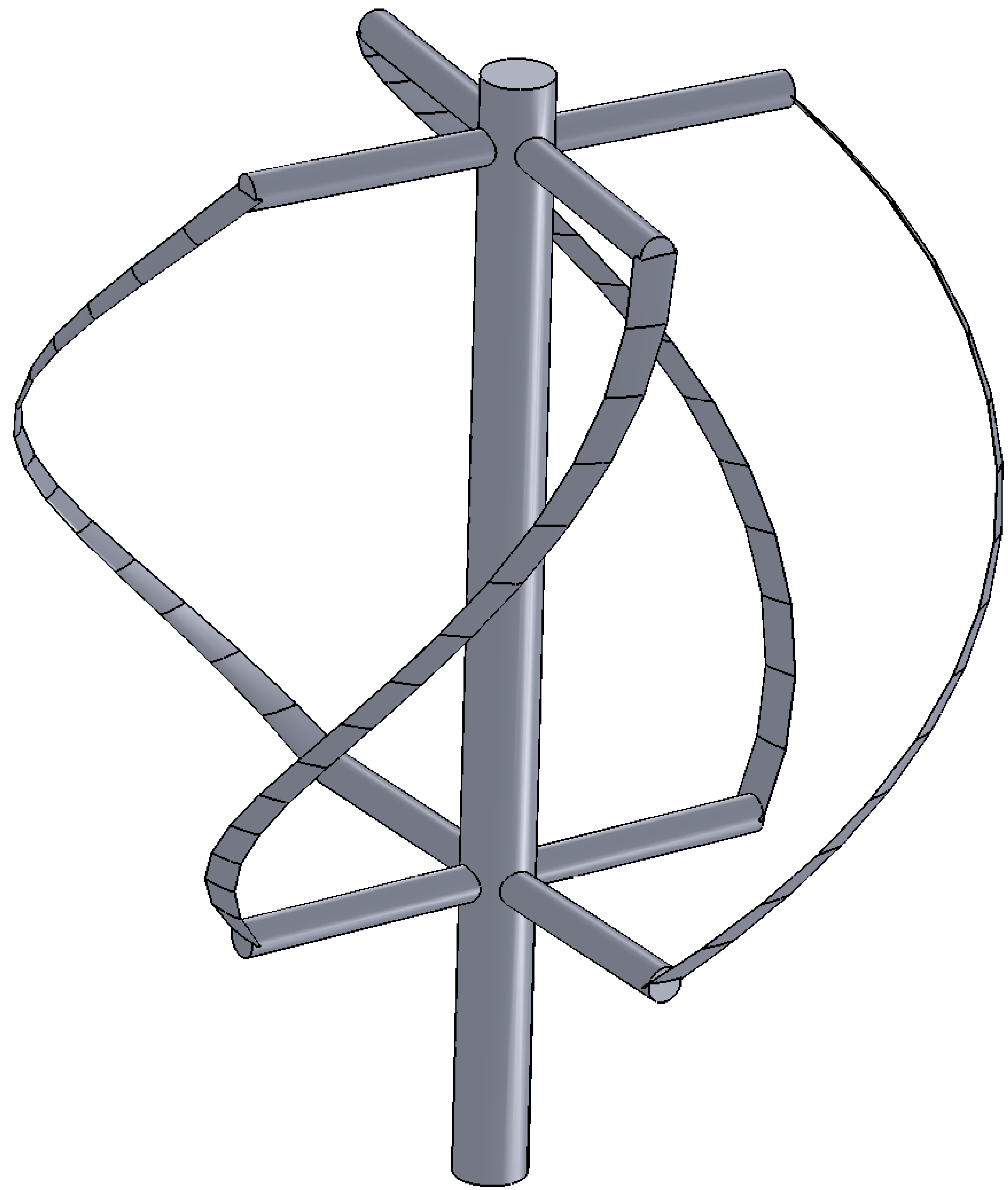
# Design Optimization of an Urban Vertical-Axis Wind Turbine

# Vertical Axis Urban Wind Turbine



# Vertical Axis Urban Wind Turbine





# MDO for Aircraft Configurations with High-fidelity (MACH)

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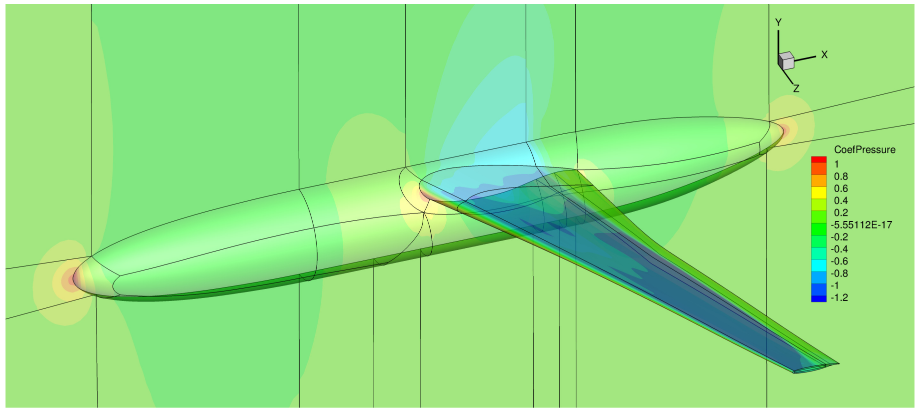
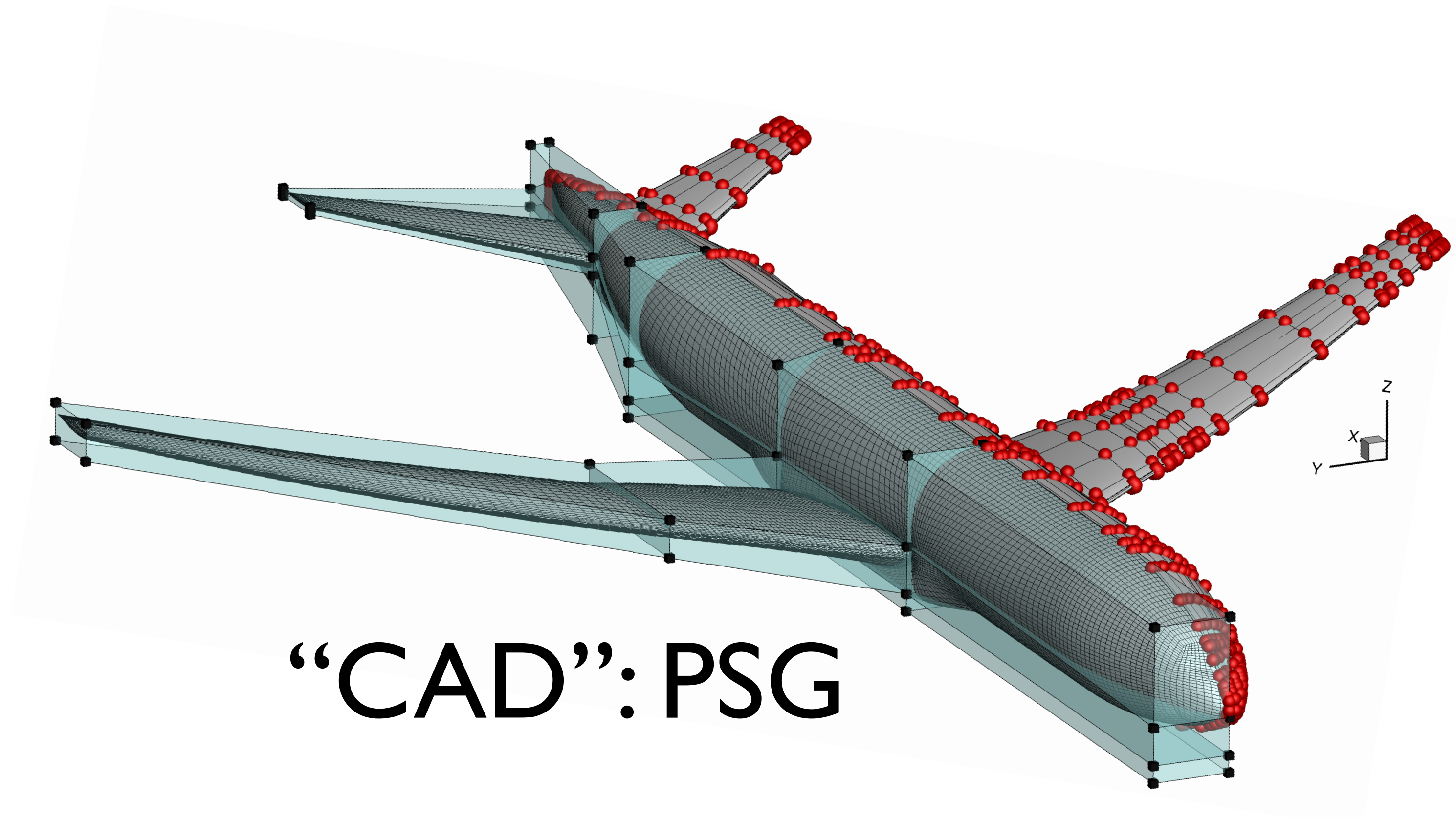
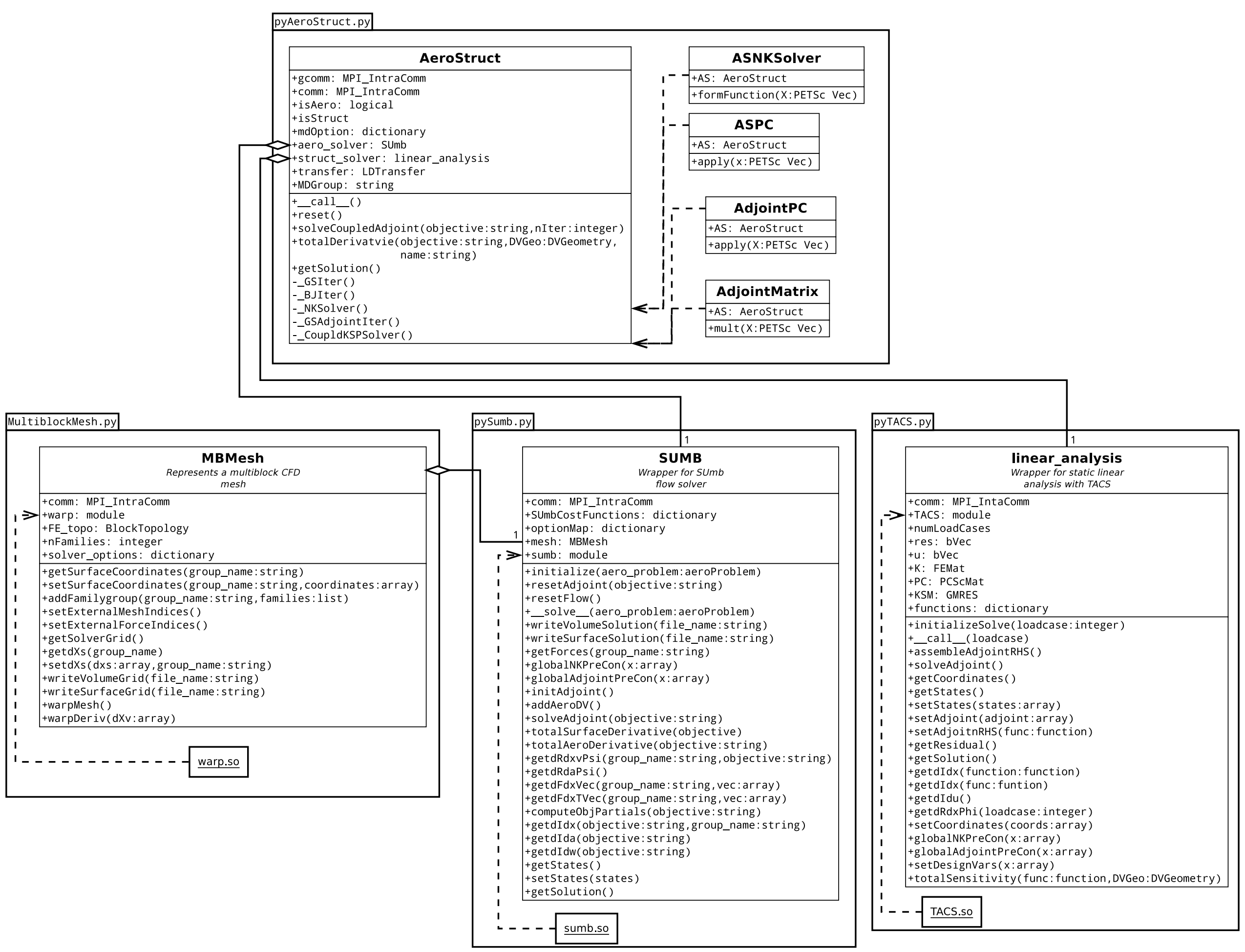


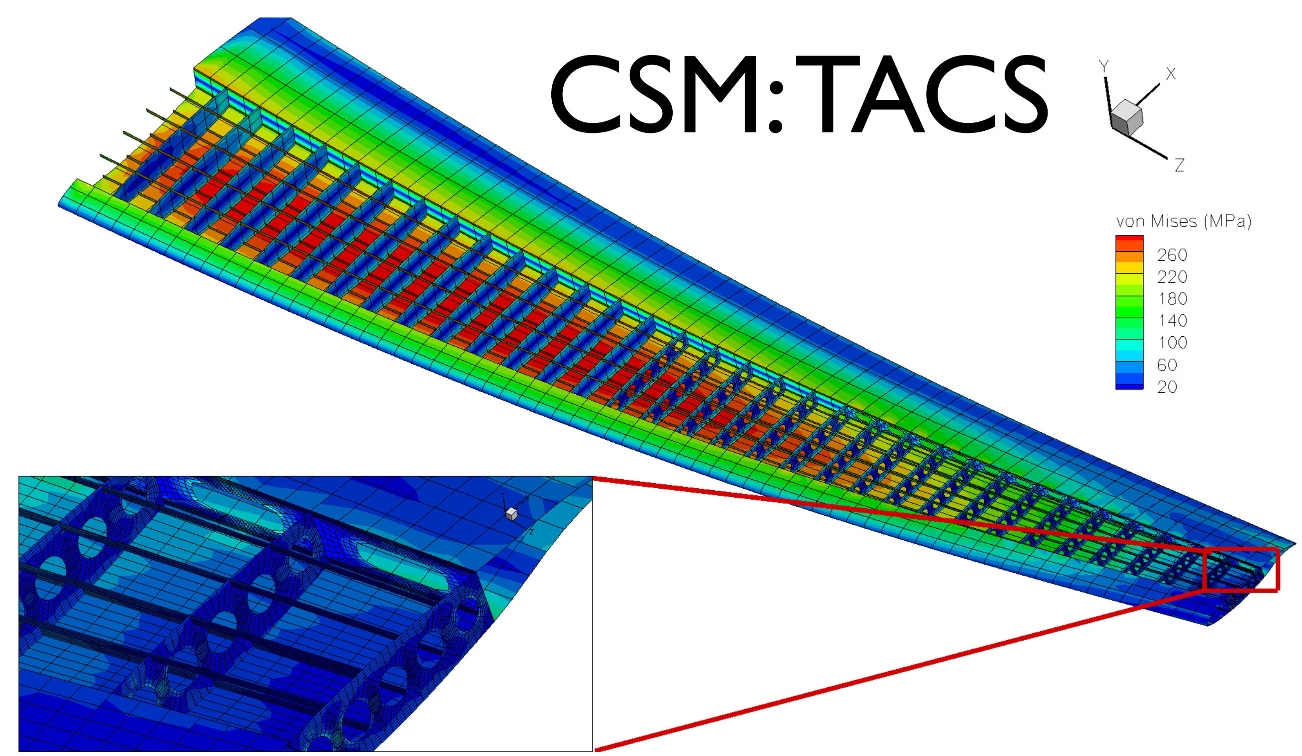

CFD: SUmb



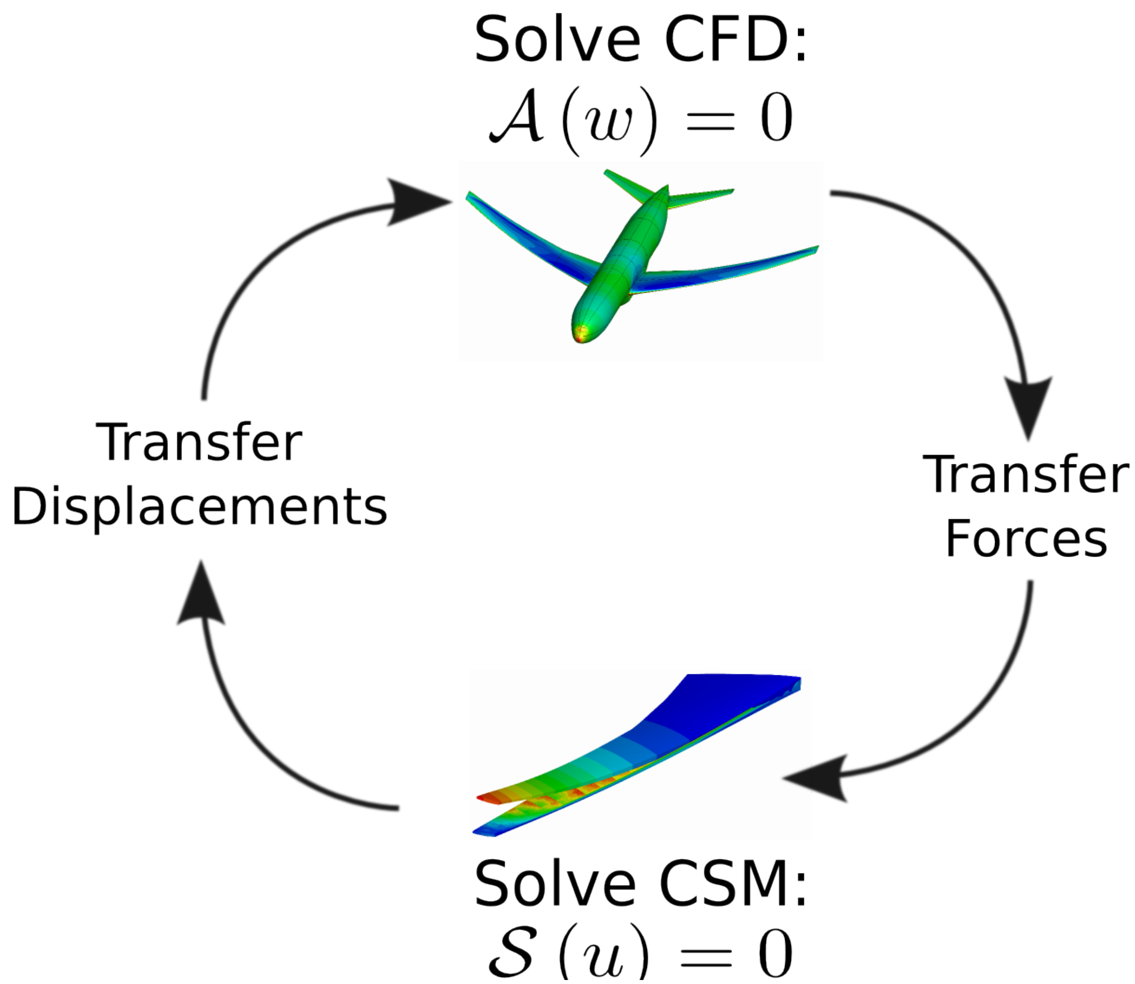
“CAD”: PSG




CSM: TACS



# Fully coupled aerostructural analysis




$\mathcal{A}$: Aerodynamic residuals
$w$: Aerodynamic states
$\mathcal{S}$: Structural residuals
$u$: Structural states

Two available methods:

- A nonlinear block Gauss–Seidel method with Aitken acceleration
- A coupled Newton–Krylov method

$$\begin{bmatrix} \frac{\partial \mathcal{A}}{\partial w} & \frac{\partial \mathcal{A}}{\partial u} \\ \frac{\partial \mathcal{S}}{\partial w} & \frac{\partial \mathcal{S}}{\partial u} \end{bmatrix} \begin{bmatrix} \Delta w \\ \Delta u \end{bmatrix} = - \begin{bmatrix} \mathcal{A}(w) \\ \mathcal{S}(u) \end{bmatrix}$$

# The coupled adjoint is the key to efficient MDO with large numbers of design variables

Adjoint equations for the aerostructural system

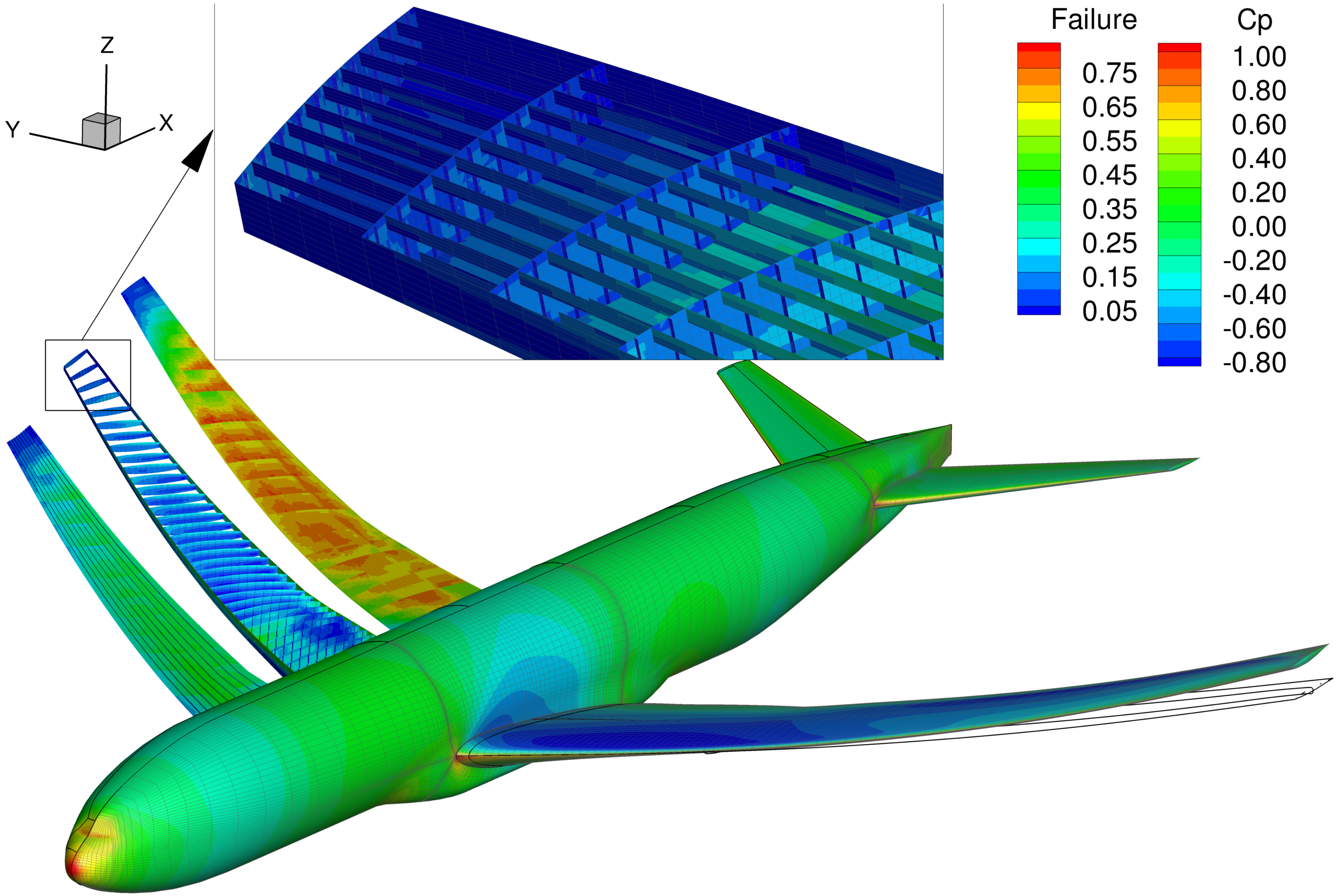
$$\begin{bmatrix} \dfrac{\partial \mathcal{A}}{\partial w} & \dfrac{\partial \mathcal{A}}{\partial u} \\ \dfrac{\partial \mathcal{S}}{\partial w} & \dfrac{\partial \mathcal{S}}{\partial u} \end{bmatrix}^T \begin{bmatrix} \psi \\ \phi \end{bmatrix} = \begin{bmatrix} \dfrac{\partial I}{\partial w} & \dfrac{\partial I}{\partial u} \end{bmatrix}^T$$

Total derivatives

$$\frac{\mathrm{d}I}{\mathrm{d}x} = \frac{\partial I}{\partial x} - \psi^T \left( \frac{\partial \mathcal{A}}{\partial x} \right) - \phi^T \left( \frac{\partial \mathcal{S}}{\partial x} \right)$$

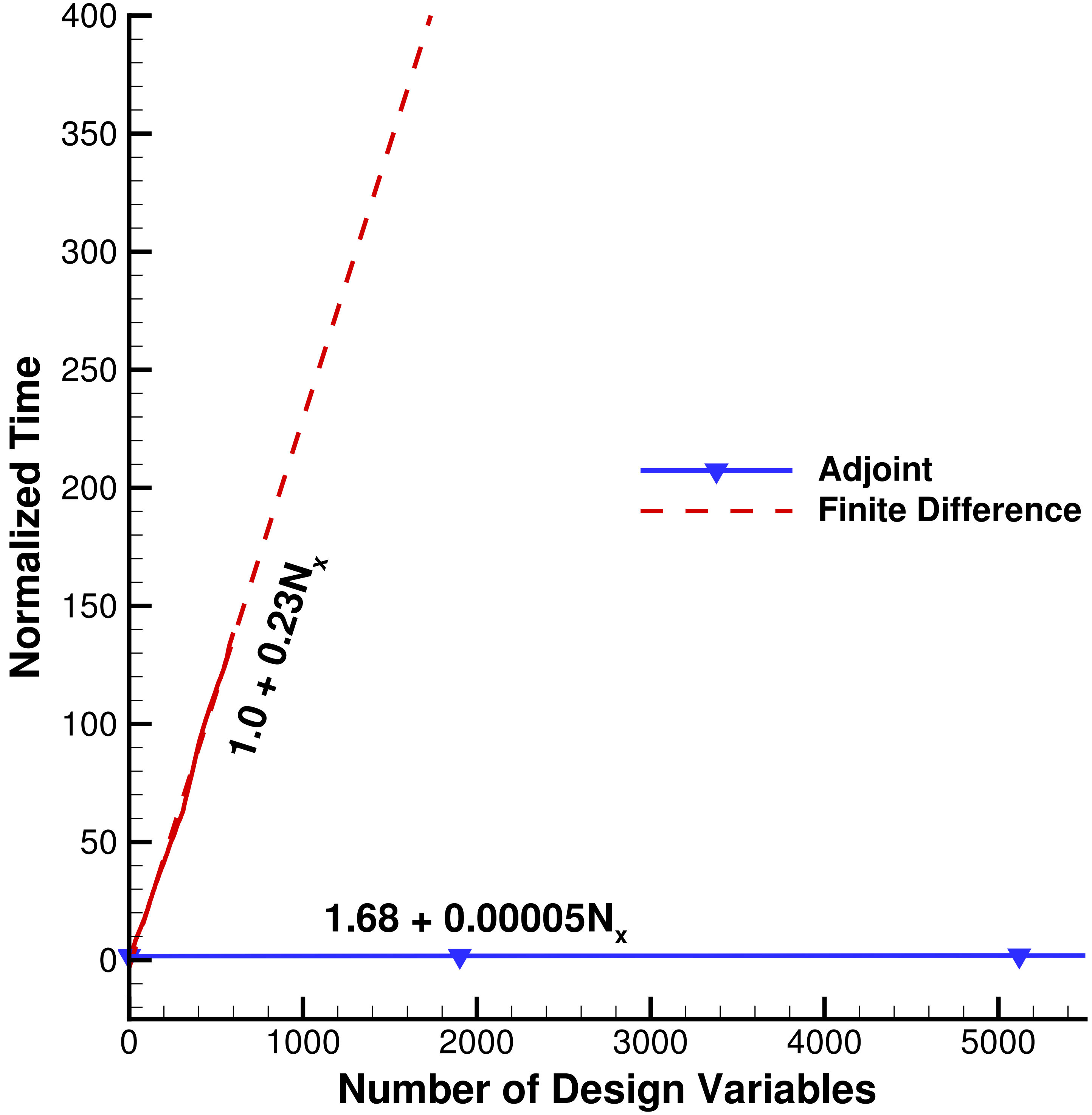
[Kenway, Kennedy and Martins, AIAAJ, 2013]

# Aerostructural Model




- NASA Common Research Model (CRM) from DPW4
- 2 million cells in CFD mesh
- Includes a structural model with 300 thousand DOFs

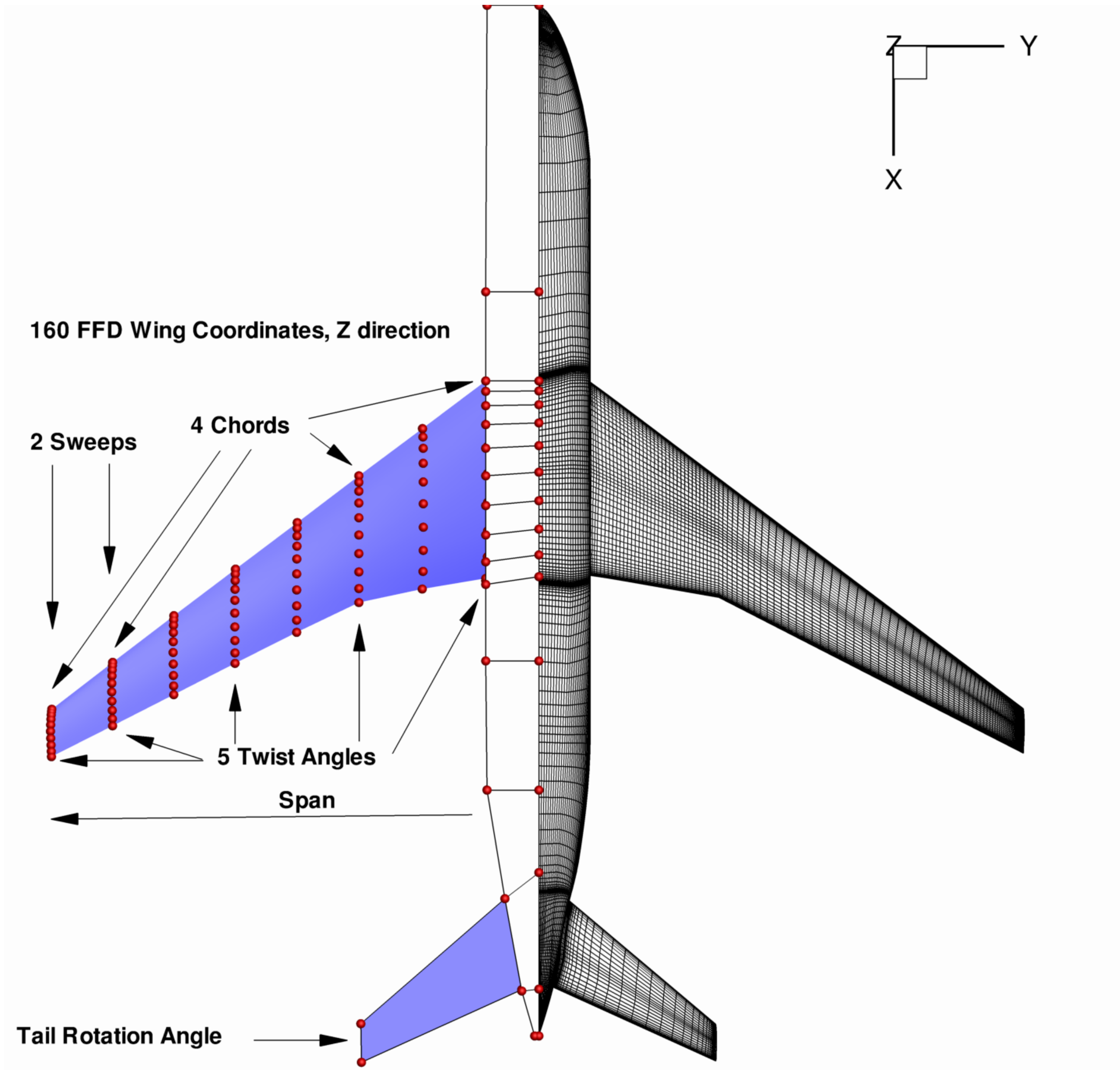
# The coupled adjoint is the key for correct and efficient gradients




- 2M CFD cells
- 300k CSM DOFs
- 56 processors
- 1 aerostructural solution = 5.5 min

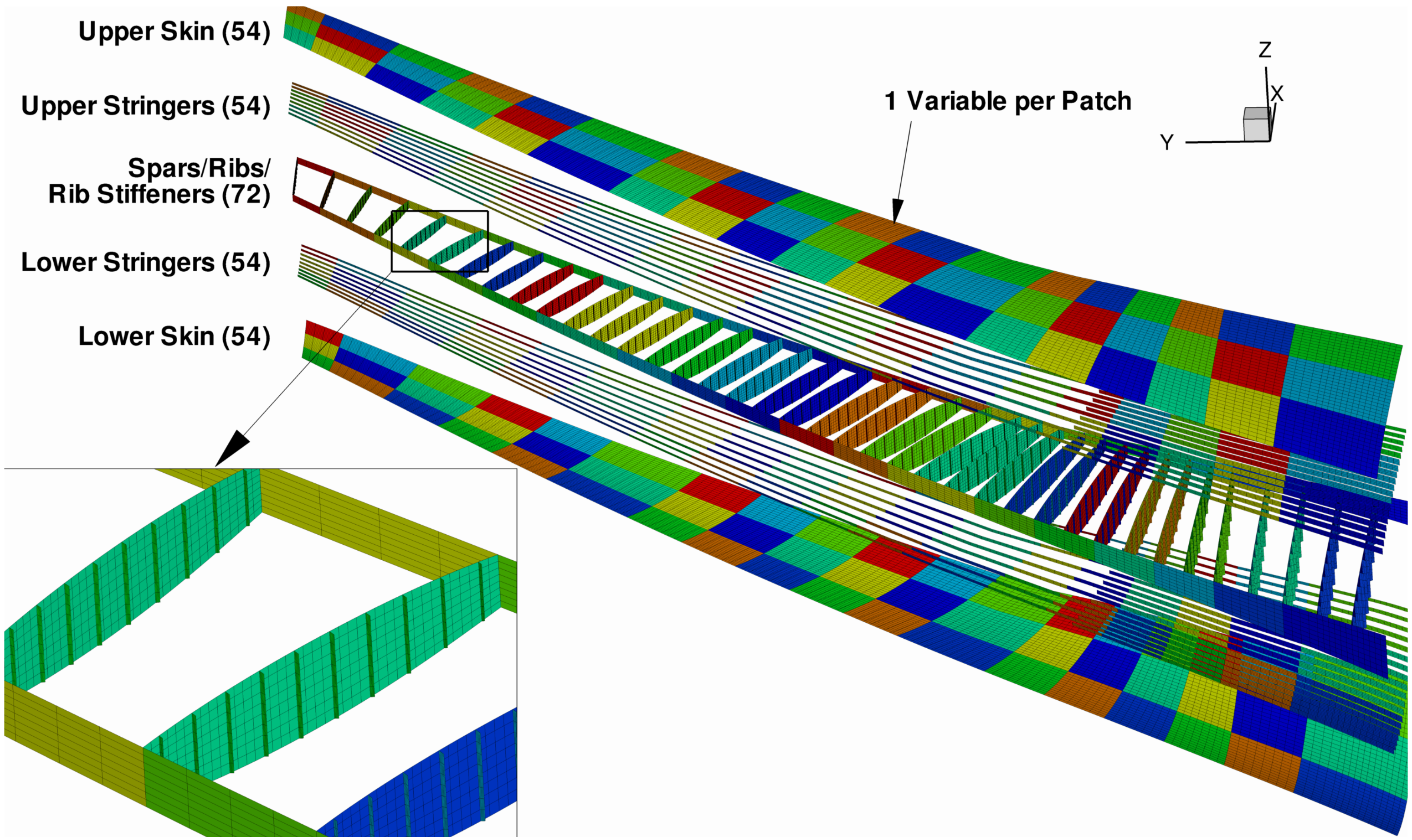
[Kenway, Kennedy and Martins, *AIAA Journal*, 2013 (forthcoming)]

# “Aerodynamic” shape variables also affect the structure directly

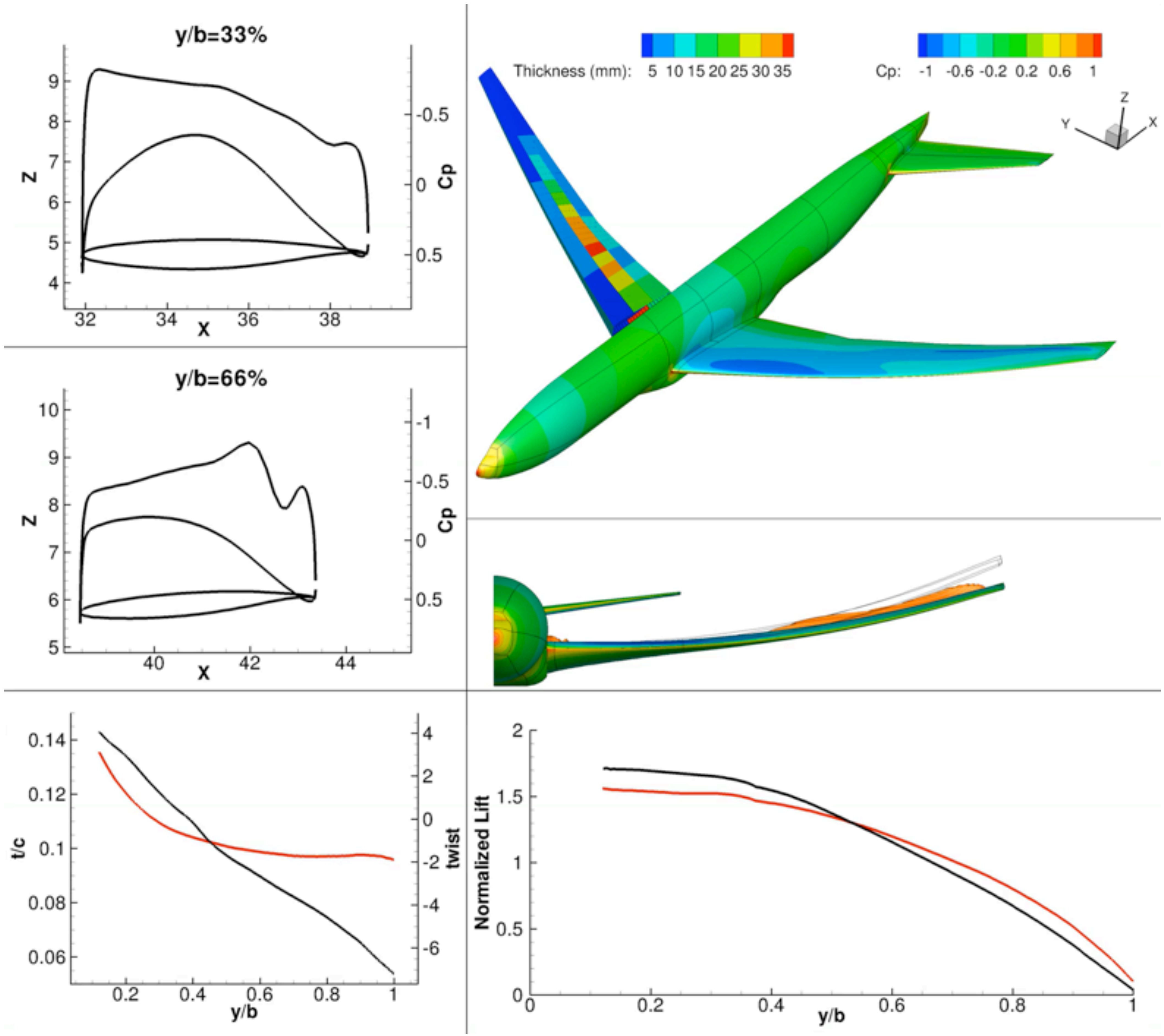



- 12 global geometric design variables
- 160 local shape design variables
- 2.1 million cell CFD mesh
- 1 angle of attack and 1 tail rotation angle for each operating condition

# Structural sizing patchwork




- 288 thickness design variables
- 300 000 structural degrees of freedom
- 476 total design variables



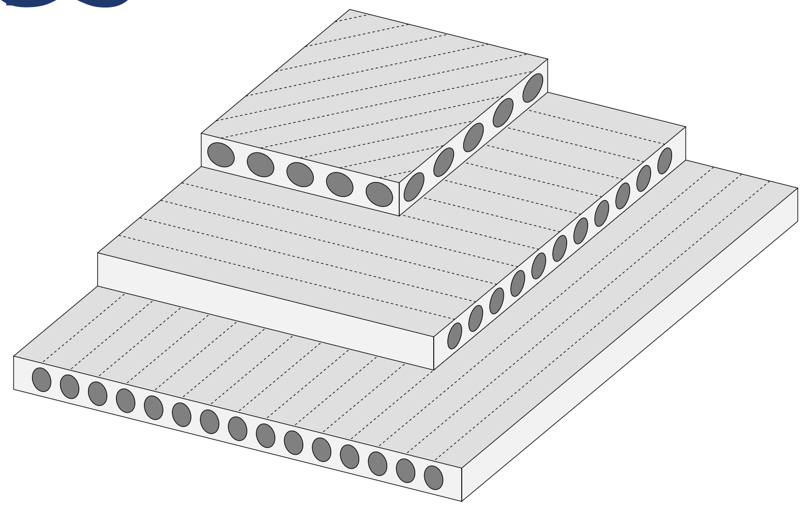

[Kenway and Martins, Journal of Aircraft, 2013 (forthcoming)]

Click here to see the video

# Composites

I have just one word for you:

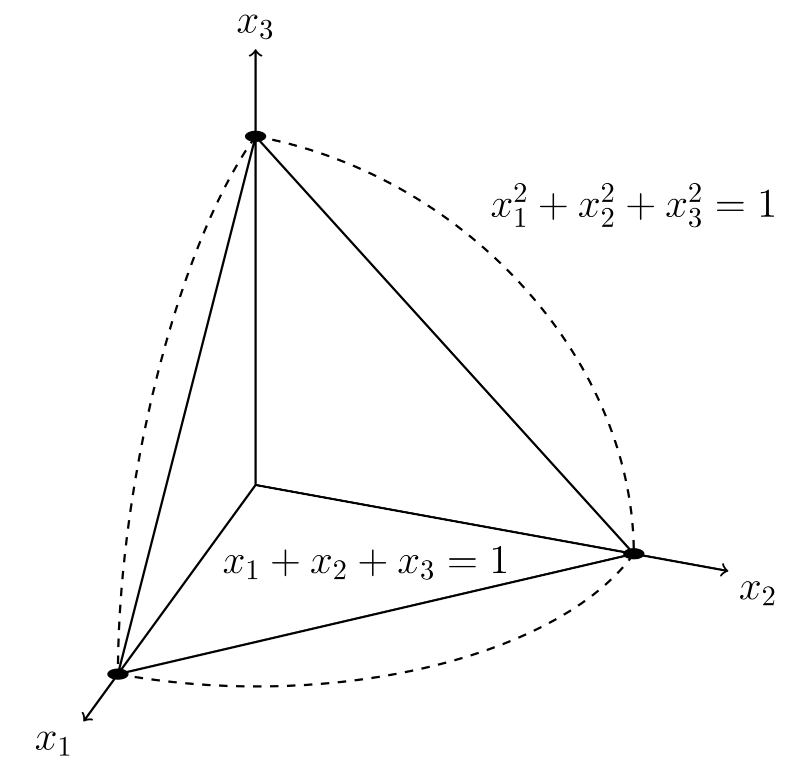
# How to tackle $10^{75}$ possible lamination sequences



- Ply-identity variables $x_i$: weights on the different possible ply selections, $\{-45°, 0°, 45°, 90°\}$
- Only one ply-identity can be active in each layer

Use two simultaneous constraints:

1. Sum of weights is 1
2. Sum of the square of the weights is 1




- Spherical constraint introduces many local minima
- Enforce spherical constraints through the use of an exact penalty function

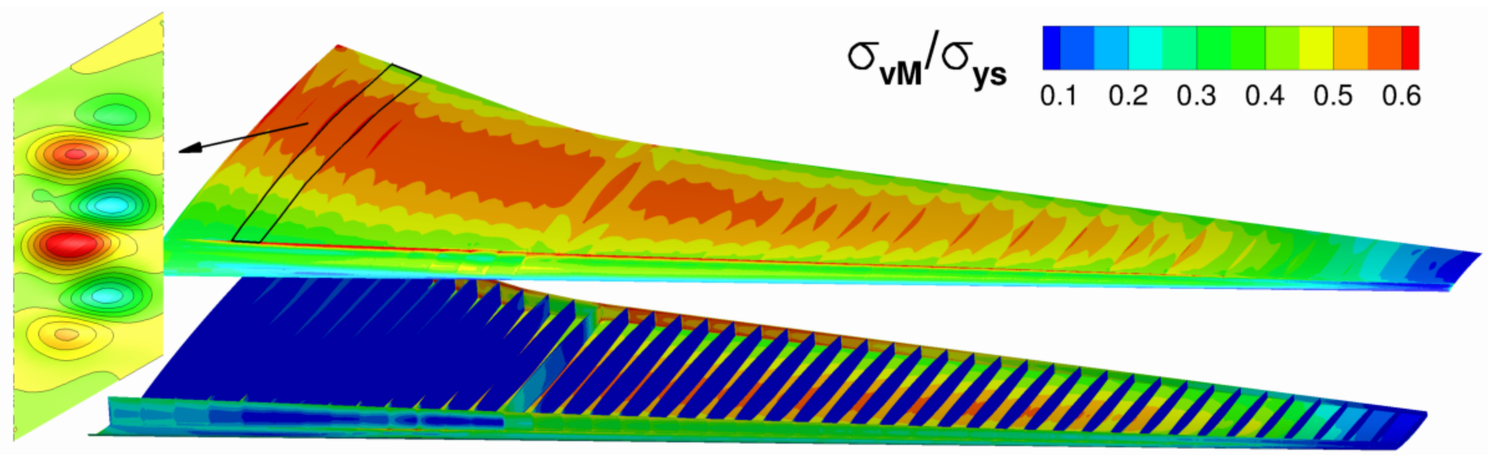
Manufacturing constraints:

- Minimum 10% ply content in all laminates
- No more than four contiguous plies at the same angle

# The design problem

- Design based on Boeing 777-200ER
- Baseline metallic wing: 29 133 kg
- Baseline composite wing: 18 131 kg
- Cruise Mach number: 0.84
- Design range: 8000 nm
- Payload: 40 000 kg
- OEW: 138 100 kg

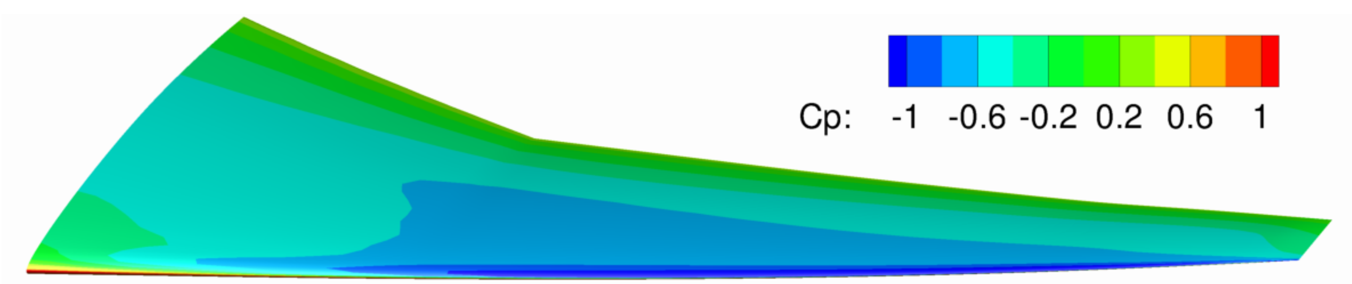
## Finite-element structural model




- 44 ribs, 2 spars
- Global finite-element model: 900 000 DOF
- Finite-strip local models with discrete stiffeners
- Smeared stiffness for FE

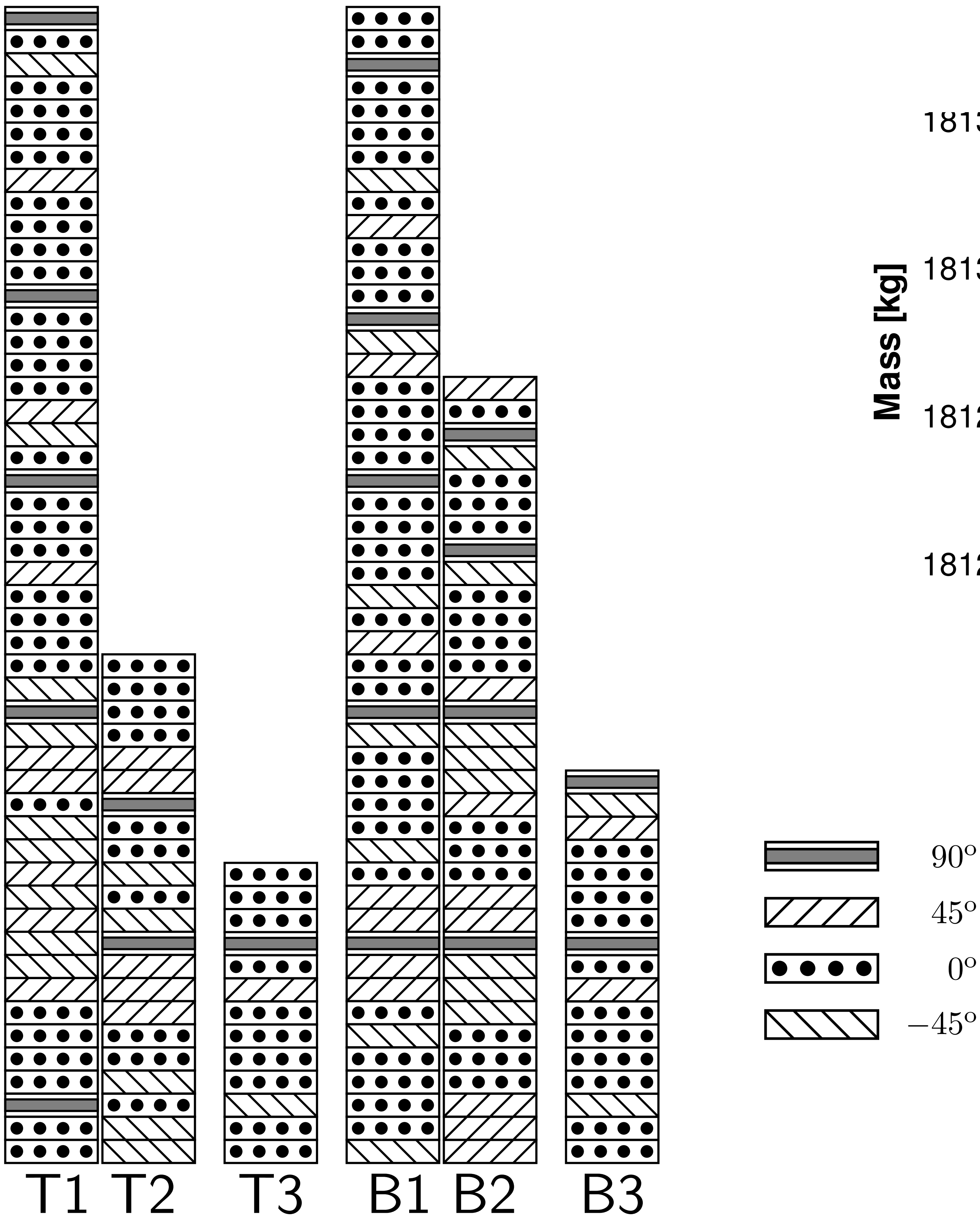
## Three-dimensional panel method

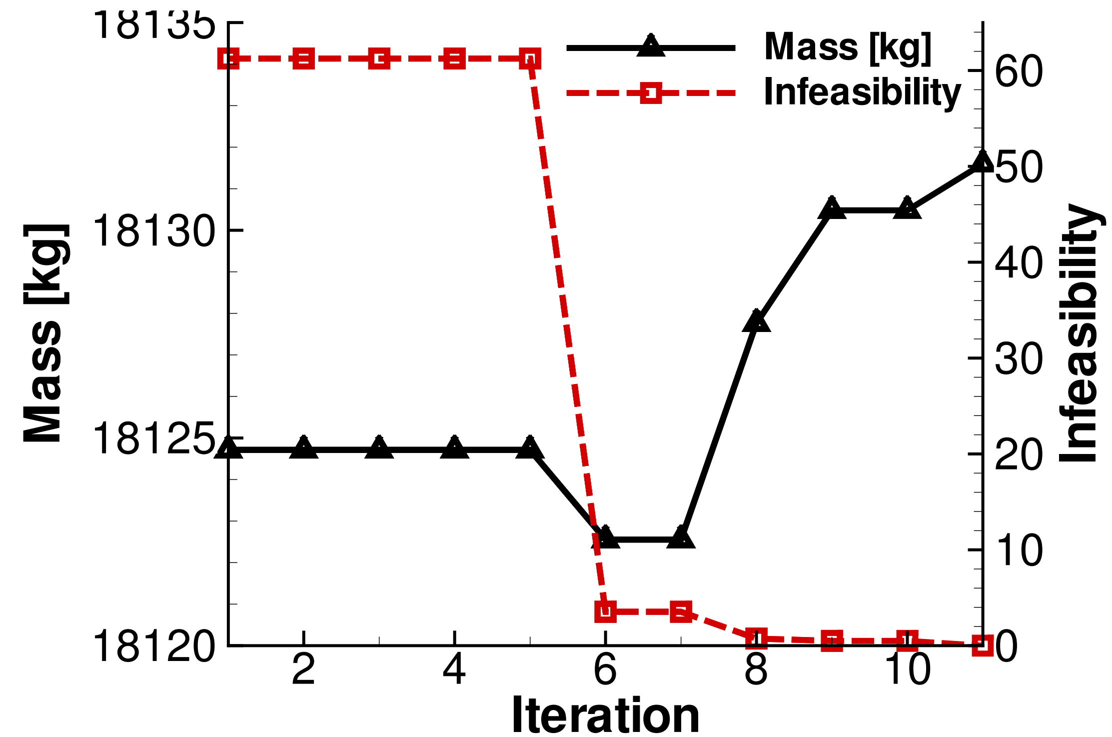
- 4200 surface panels
- Profile and wave drag corrections

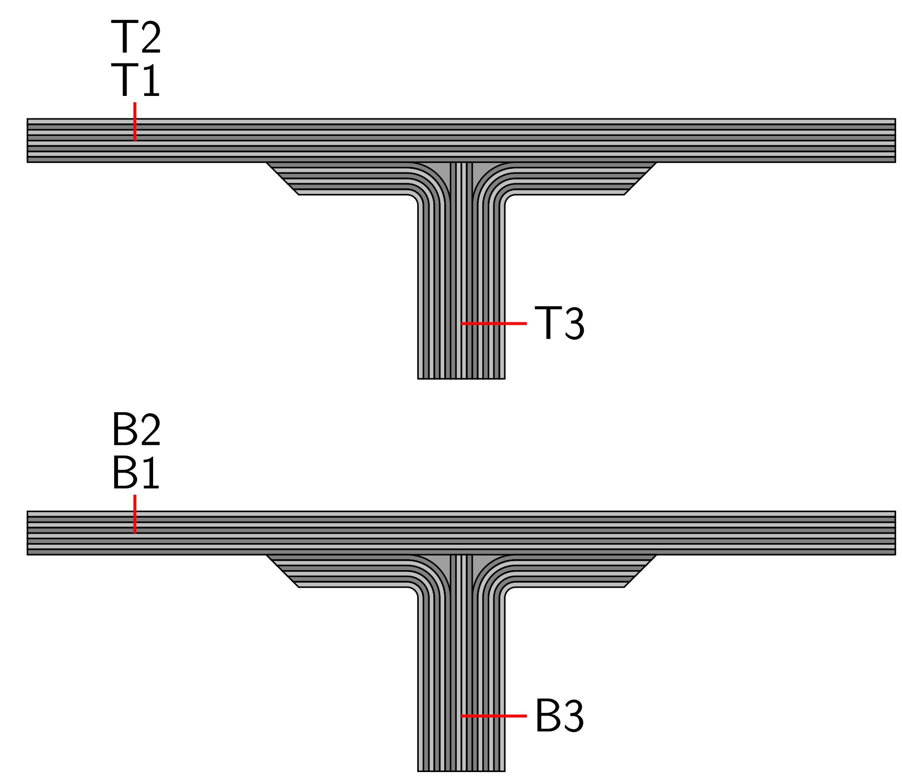



[Kennedy and Martins, *AIAA MAO*, 2012]

# How these results stack up

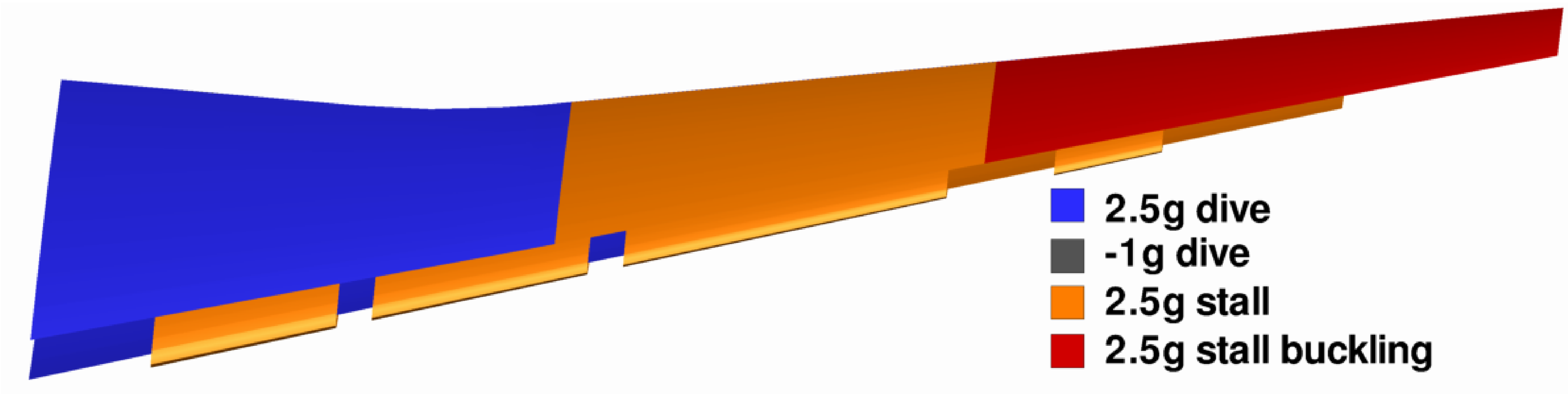


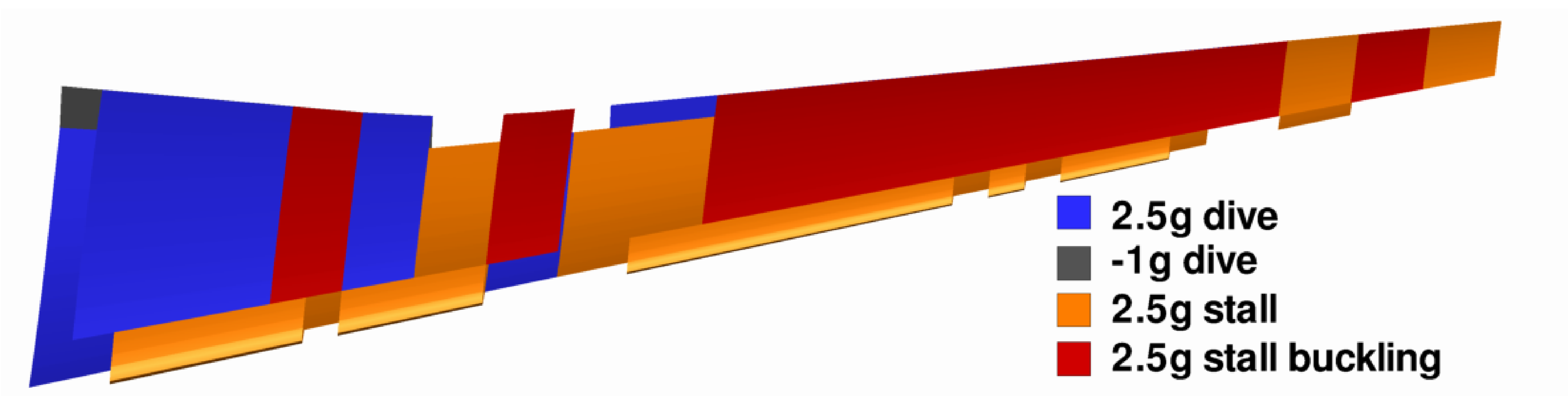



# The active structural constraints

Metallic wing




Composite wing




- Only the 100% fuel load conditions are active
- Composite inboard buckling conditions: local buckling of the stiffeners

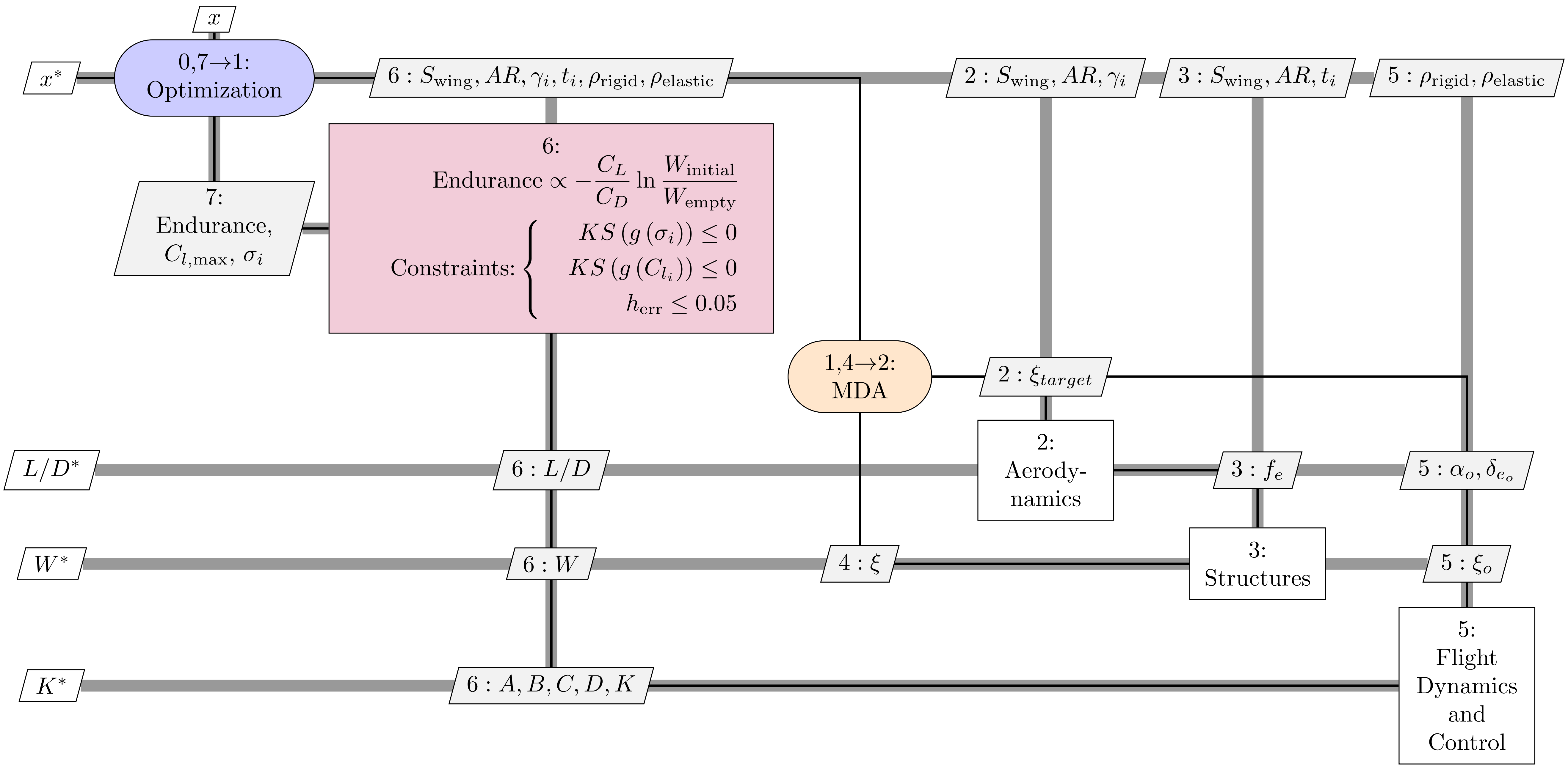
[Kennedy and Martins, *AIAA MAO*, 2012]

Why can't we just all work together?

Aerodynamic shape + Structural sizing + Control gains =

# Aeroservoelastic Optimization

# This aeroservoelastic optimization considers maneuver and gust loads




[Haghighat, Liu and Martins, *Journal of Aircraft*, 2012]

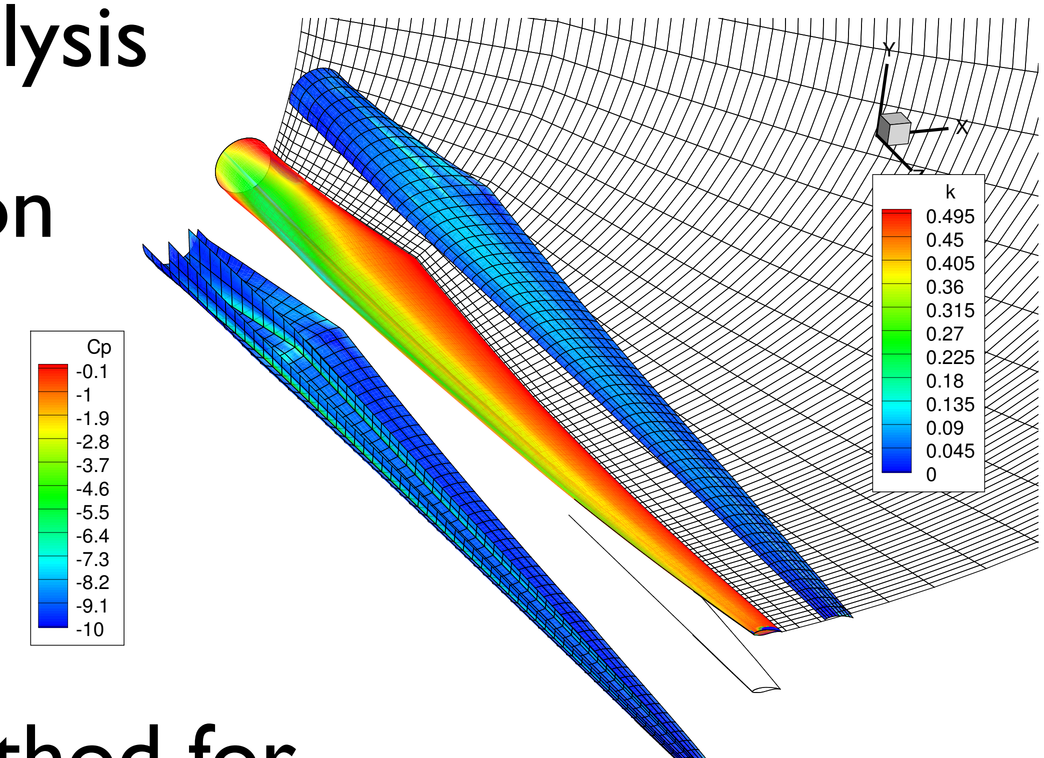
# Aeroservoelastic optimum was significantly better than the aerostructural one...

Optimization results with and without load alleviation system.

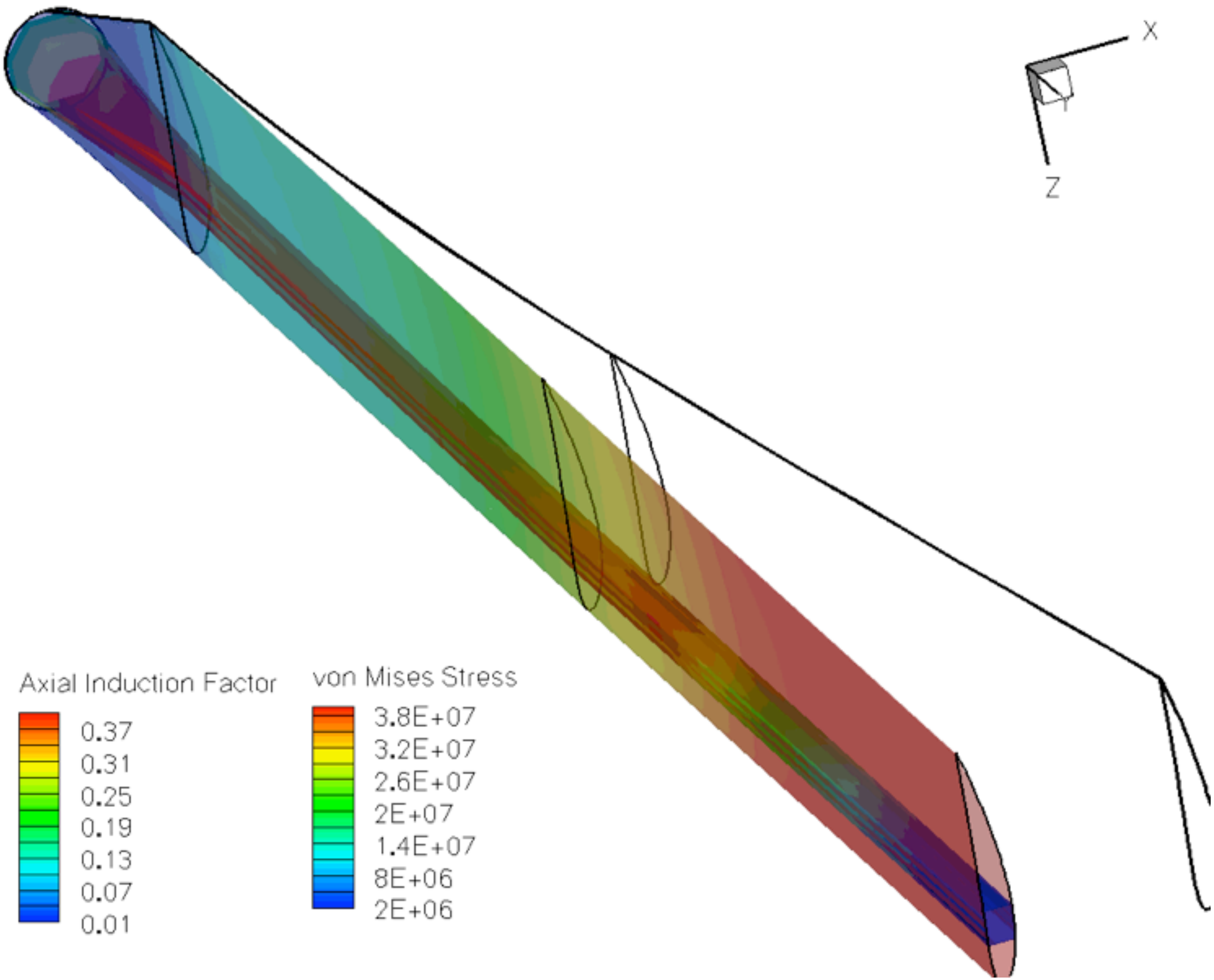
| Load alleviation | Off | On | |
|---|---|---|---|
| $S_{\text{ref}}$ $(m^2)$ | 219.18 | 191.47 | 14.5% smaller |
| $AR$ | 13.98 | 14.03 | |
| $L/D$ | 34.29 | 34.37 | |
| $q_{\text{elastic}}$ | 1499.95 | 1499.88 | |
| $q_{\text{rigid}}$ | 90.63 | 75.71 | |
| Wing mass (kg) | 13,378 | 7,817 | 41.5% lighter |
| Endurance factor | 31.90 | 38.83 | 21.7% higher |

# Current and Future Work

- Create a detailed FEM of an NREL turbine blade
- Implement a low-speed preconditioner for the CFD solver
- Validate the CFD, FEA, and coupled analysis
- Formulate a relevant design optimization problem
- Optimize composite layup for optimal aeroelastic tailoring
- Use of nonlinear frequency domain method for coupled unsteady analysis
- Add control for aeroservoelastic optimization



# Thank you!




http://mdolab.engin.umich.edu/publications